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First determination of the spin-parity of the $\Xi_c(3055)^{+(0)}$ baryons

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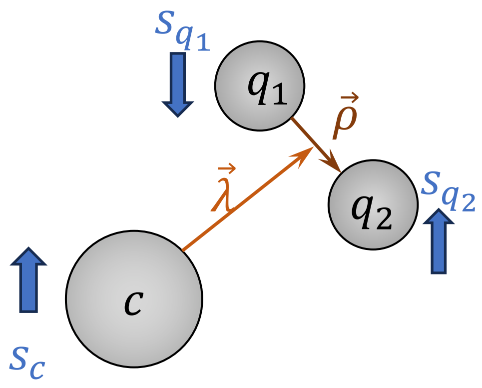
in representative of the LHCb Collaboration

Outline

- Motivation & overview
- Event selection
- Mass fit & signal extraction
- Amplitude analysis
- J^P determination of $\Xi_c(3055)^{+(0)}$
- Systematics
- Summary

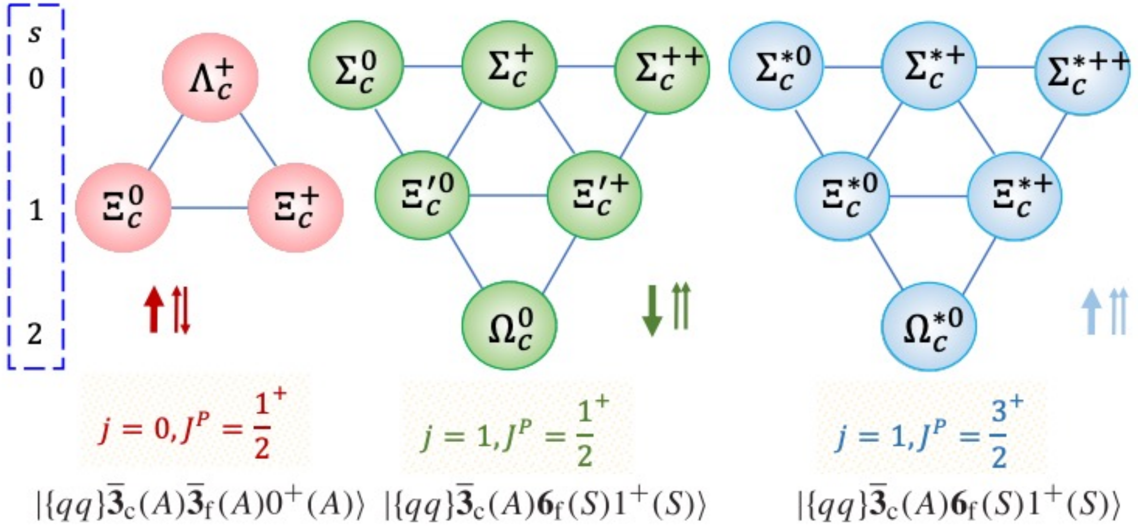
Introduction

Singly heavy baryons



- Good lab for non-perturbative QCD
  - Many undiscovered/determined states
  - Various theoretical explanations
- **Pinning down the state:**
  - Mass, width, decay modes
  - Spin-parity
  - Decay parameter

- Singly heavy baryon:
  - A heavy quark (c,b) and two light quarks (u,d,s)
  - In the relative frame:
    - Dynamics governed by the light quark pairs (*di-quark*)
- Rich spectrum:
  - Ground states: $\bar{3}_F$ (Λ, Ξ) / $6_F(\Sigma, \Xi', \Omega)$
  - Excitation modes: λ/ρ-mode



Decay parameter

- Under helicity basis:

$$\alpha_{\Xi_b \to \Xi_c^{**}\pi} \equiv \frac{|H_\uparrow|^2 - |H_\downarrow|^2}{|H_\uparrow|^2 + |H_\downarrow|^2}$$

  - Reflect parity violation in the transition

- If the initial (Ξ_b) & final (Ξ_c^{**}) particle have similar structure:
  - Governed by $b \to c$ weak decay
  - Pure parity violation, $\alpha_{\Xi_b \to \Xi_c^{**}\pi} \sim -100\%$

- If not: deviation from -100%

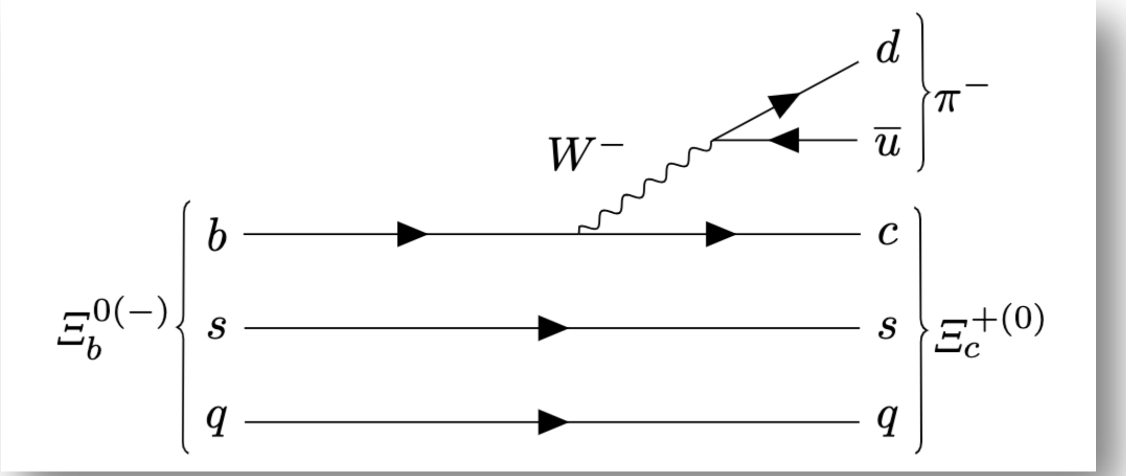
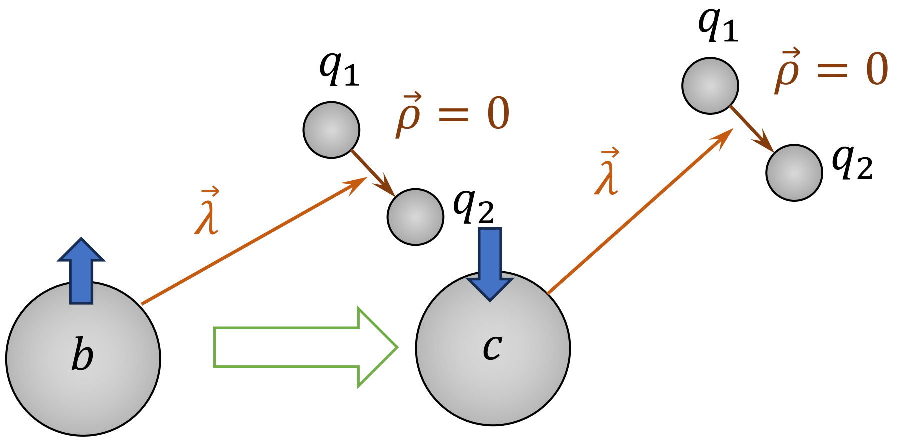


TABLE XIV: The predicted up-down asymmetries of $\mathcal{B}_b \to \mathcal{B}_c P$ decays. The asymmetries are given in unit of %. The asterisks in the first column indicate that the baryons in the final states are radial excited.

Type	Mode	$P=\pi^-$	$P=K^-$	$P=D^-$	$P=D_s^-$
(i)	$\alpha(\Lambda_b \to \Lambda_c P)$	$-99.99^{+2.24}_{-0.00}$	$-99.98^{+2.41}_{-0.00}$	$-98.47^{+8.91}_{-1.52}$	$-98.06^{+9.41}_{-1.87}$
(i)	$\alpha(\Xi_b^0 \to \Xi_c^+ P)$	$-99.99^{+2.24}_{-0.00}$	$-99.97^{+2.41}_{-0.00}$	$-98.40^{+9.01}_{-1.59}$	$-97.96^{+9.52}_{-1.96}$
(i)	$\alpha(\Xi_b^- \to \Xi_c^0 P)$	$-99.99^{+2.24}_{-0.00}$	$-99.97^{+2.41}_{-0.00}$	$-98.39^{+9.01}_{-1.59}$	$-97.96^{+9.53}_{-1.96}$
(i)*	$\alpha[\Lambda_b \to \Lambda_c(2765)P]$	$-100.00^{+2.14}_{-0.00}$	$-99.98^{+2.39}_{-0.00}$	$-96.61^{+10.76}_{-3.32}$	$-95.54^{+11.49}_{-4.46}$
(ii)	$\alpha(\Omega_b \to \Omega_c P)$	$59.92^{+9.88}_{-9.22}$	$59.93^{+9.88}_{-9.22}$	$59.95^{+14.95}_{-13.54}$	$59.90^{+14.95}_{-13.53}$
(ii)*	$\alpha[\Omega_b \to \Omega_c(3090)P]$	$60.02^{+9.88}_{-9.23}$	$60.02^{+9.88}_{-9.23}$	$59.49^{+14.93}_{-13.47}$	$59.23^{+14.92}_{-13.43}$
(iii)	$\alpha[\Lambda_b \to \Lambda_c(2595)P]$	$-98.86^{+4.77}_{-1.04}$	$-98.84^{+4.79}_{-1.05}$	$-97.86^{+9.63}_{-2.03}$	$-97.57^{+9.93}_{-2.25}$
(iii)	$\alpha[\Xi_b^0 \to \Xi_c^+(2790)P]$	$-99.13^{+4.44}_{-0.84}$	$-99.12^{+4.44}_{-0.84}$	$-98.58^{+8.77}_{-1.42}$	$-98.39^{+9.02}_{-1.59}$
(iii)	$\alpha[\Xi_b^- \to \Xi_c^0(2790)P]$	$-99.13^{+4.44}_{-0.84}$	$-99.12^{+4.44}_{-0.84}$	$-98.58^{+8.76}_{-1.42}$	$-98.39^{+9.02}_{-1.59}$
(iii)*	$\alpha[\Lambda_b \to \Lambda_c(2940)P]$	$-98.86^{+4.76}_{-1.03}$	$-98.84^{+4.78}_{-1.05}$	$-97.04^{+10.41}_{-2.81}$	$-96.36^{+10.94}_{-3.60}$

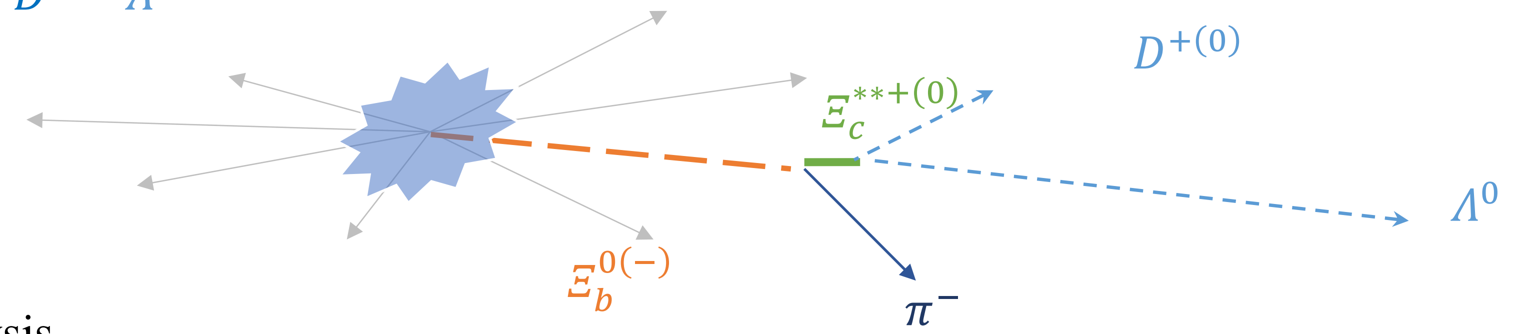
Unit : %



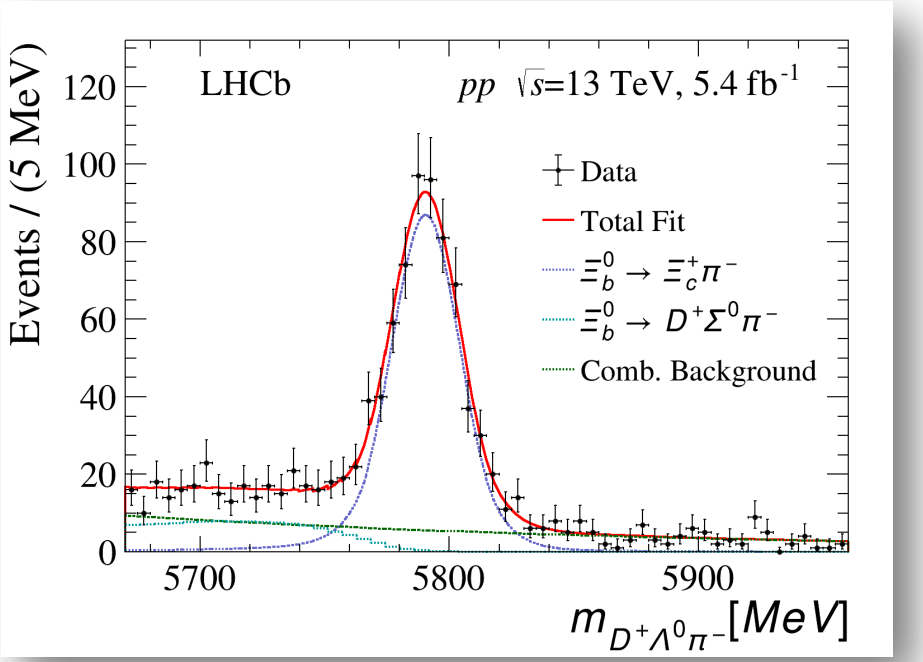
Ref:1811.09265

Analysis overview

- In $\Xi_b^{0(-)} \to \Xi_c^{**+(0)}\pi^-$ decay, where $\Xi_c^{**+(0)} \to D^{+(0)}\Lambda^0$
  - $D^{+(0)} \to K\pi\pi(K\pi)$
  - $\Lambda^0 \to p\pi$ (LL/DD categories)



- Run2 2016-18 data sample
  - LL/DD separated before amplitude analysis

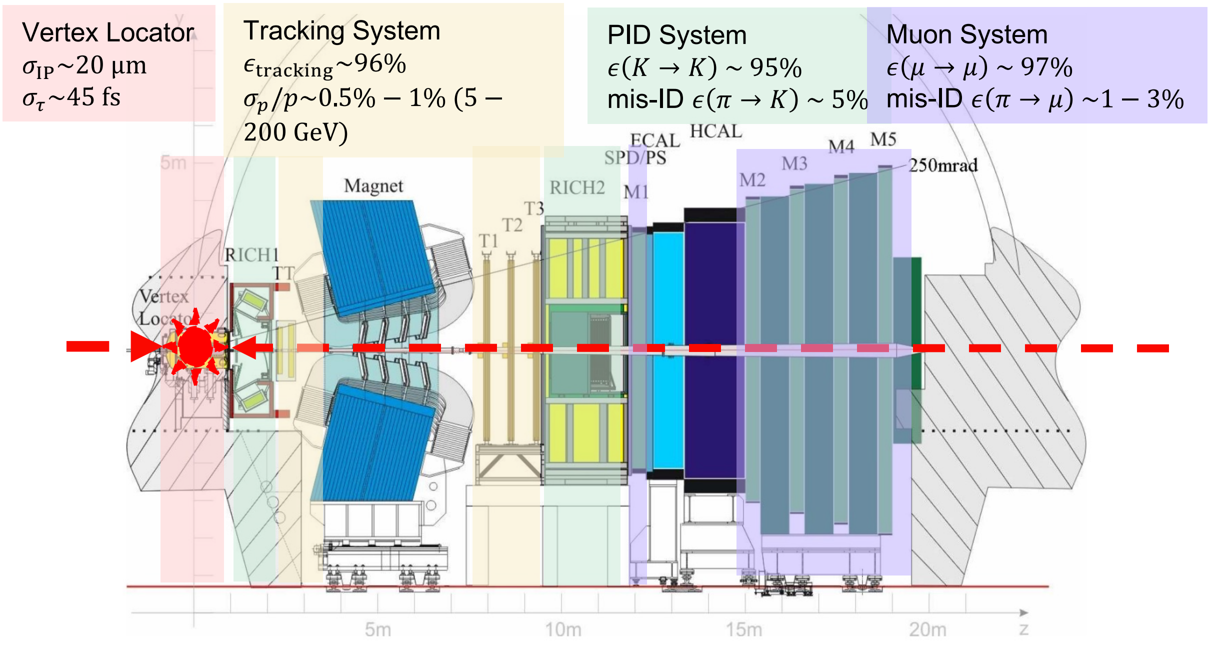


- Strategy:
  1. Event selection
  2. Signal extraction (Ξ_b mass fit)
  3. Amplitude analysis
  4. Spin-parity determination
     - Validation (toy study)
  5. Systematic uncertainties

The LHCb Detector (Run2)

Large **H**adron **C**ollider **b**eauty experiment：

- Single-arm forward region:
  - Designed for collecting heavy flavor events
  - b-Factory
- Dedicated vertex detector:
  - Excellent vertex, impact parameter resolution
- Tracking system: good momentum resolution
- PID system: hadron and muon identification
- Hardware & Software trigger



[JINST 3 (2008) S08005] [IJMPA 30 (2015) 1530022]

Event selection

Pre-selection

- Stripping lines 28r2/29r2/34:
  - Lb2DLambda0LLpi, Lb2DLambda0DDpi,
  - Xib2D0Lambda0LLpi, Xib2D0Lambda0DDpi

Table 1: Trigger requirements

L0	Hadron TOS || Global TIS
Hlt 1	TrackMVA || TwoTrackMVA
Hlt 2	Topo2/3/4Body TOS

Table 2: Pre-selections

Particles	Requirements
K, π	$ProbNNghost < 0.8$
π	$ProbNNpi > 0.1$
K	$ProbNNk > 0.2$
$D\ invariant\ mass$	$\lvert m_{K\pi(\pi)} - M^{PDG}_{D^{+(0)}} \rvert < 20$ MeV
$\Lambda^0\ invariant\ mass$ (LL/DD)	$\lvert m_{p\pi} - M^{PDG}_{\Lambda} \rvert < 6$ MeV
$\Xi_c^{+(0)}\ invariant\ mass$ [MeV] ($\Xi_b^{0(-)}, D^{+(0)}, \Lambda\ constrained\ with\ DTF$)	$m_{\Xi_c^{+(0)}} < 3400$ MeV

Table 3 : Training Variables

Particle	Variables
Ξ_b	$p_T, \chi^2_{IP}, \chi^2_{FD}$, $DIRA, \eta, \chi^2_{vtx}$
Λ^0	p_T, FD, $\chi^2_{vtx}, \chi^2_{FD}, \chi^2_{IP}$ (LL only)
D	p_T, χ^2_{IP}
$\pi^-\ from\ \Xi_b$	p_T, χ^2_{IP}

MVA selection

- Training samples
  - Signal from MC within signal region :

$$\left|m_{D\Lambda\pi} - m_{\Xi_b}^{PDG}\right| < 50MeV$$

  - Background from upper mass sideband of data :

$$300\ MeV < m_{D\Lambda\pi} - m_{\Xi_b}^{PDG} < 700\ MeV$$

- MLP evaluated for Ξ_b^0/Ξ_b^-, LL/DD separately

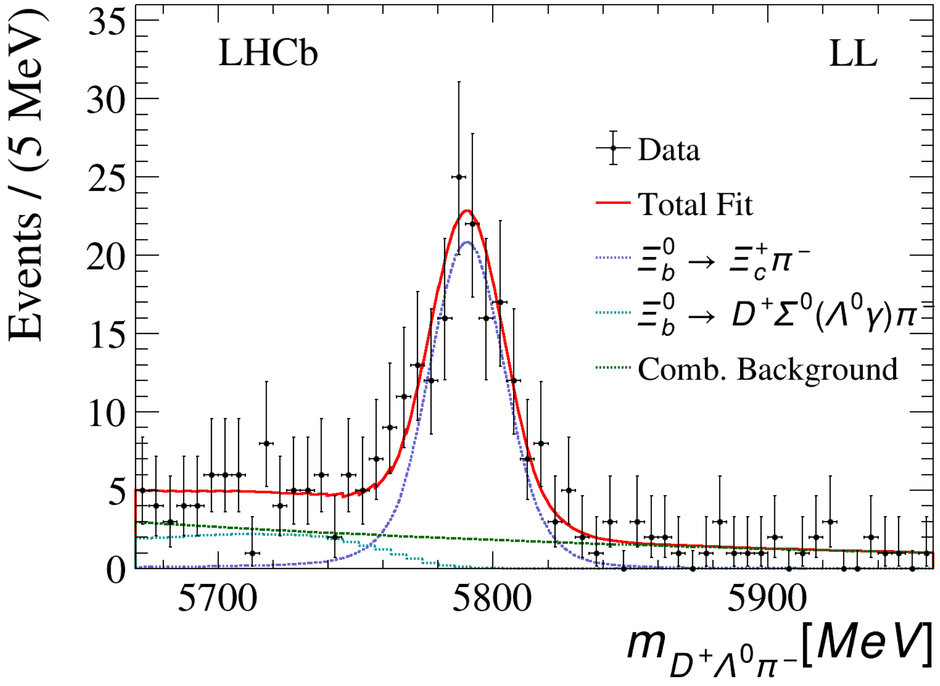
- Optimized with FoM dedicated to amplitude analysis:

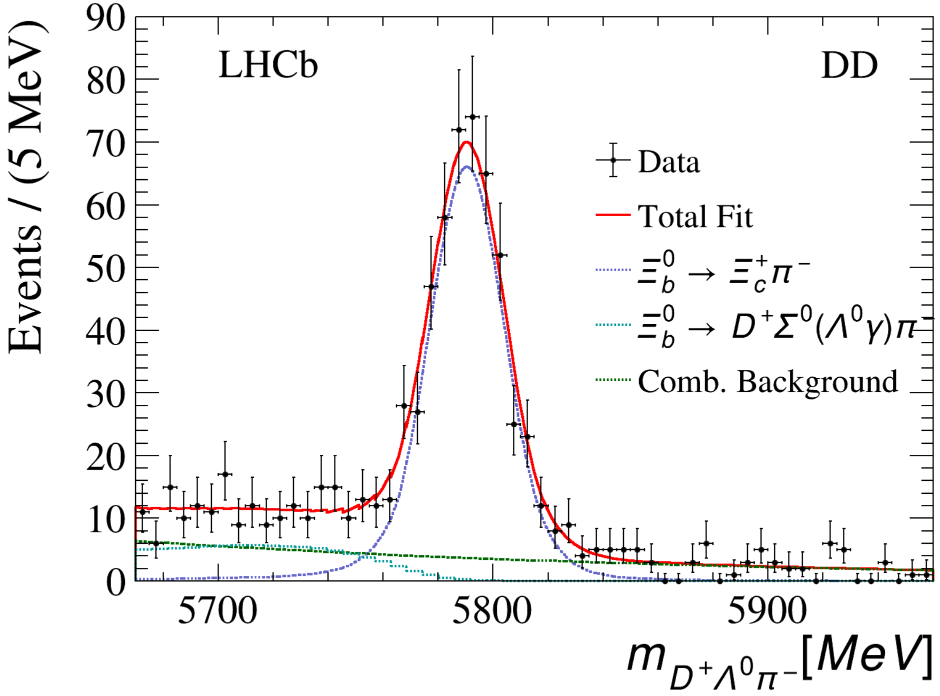
$$F(t) = \frac{S(t)}{S(t)+B(t)} \times \frac{S(t)}{\sqrt{S(t)+B(t)}}$$

Table 4 : Training Variables

Particle	Variables
Ξ_b	$p_T, \chi^2_{IP}, \chi^2_{FD}$, $DIRA, \eta, \chi^2_{vtx}$
Λ^0	p_T, FD, $\chi^2_{vtx}, \chi^2_{FD}$, χ^2_{IP} (LL only)
D	p_T, χ^2_{IP}
$\pi^-\ from\ \Xi_b$	p_T, χ^2_{IP}

Ξ_b mass fit





- Signal model: Gaussian + DSCB (parameters determined from MC)
- Partial reconstruction: shape from fast simulation
- Combinatorial background: exponential

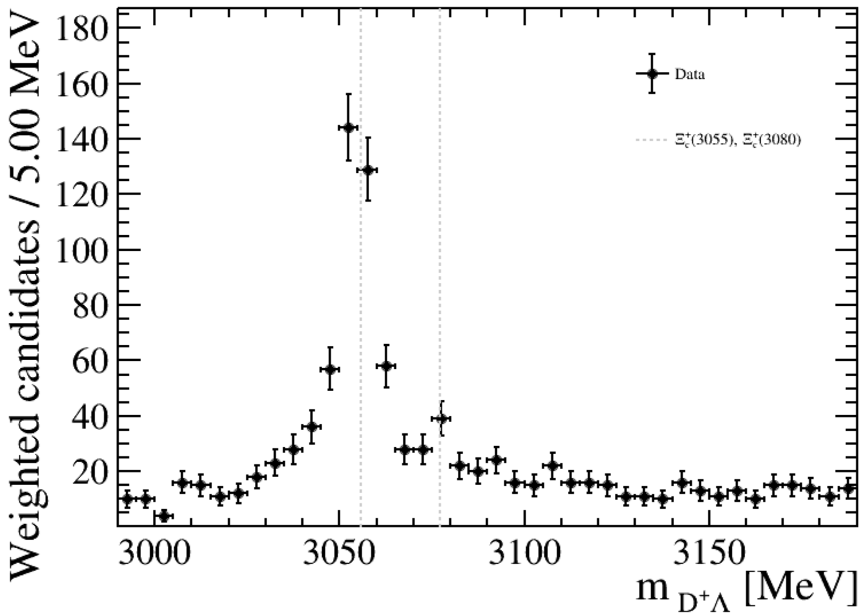
➢ Simultaneously for LL & DD

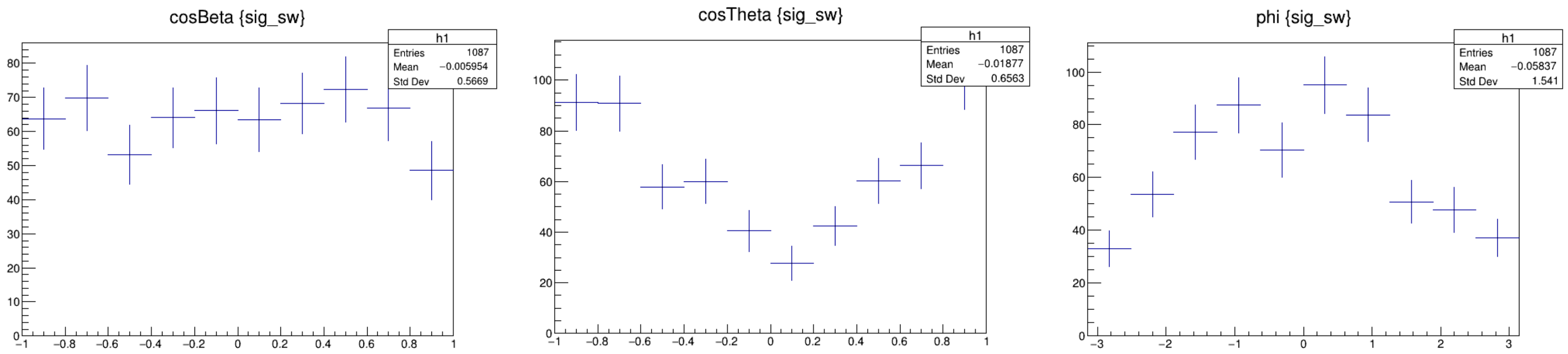
PDG value: 5791.9 ± 0.5 MeV

Parameters	Fit Result(DD)	Fit Result(LL)
$\mu_{\Xi_b^0}$	5790.4±0.8 MeV	
$\sigma_{\Xi_b^0}$	14.1±0.9 MeV	
signal yield	411±24	108±13

Extracted spectrum

- Extract pure Ξ_b with sPlot method 10.1016/j.nima.2005.08.106
  - $\Xi_c(3055)^+$ observed
  - $\Xi_c(3080)^+$ with significance of 4.4σ
  - Non-resonance component
- Dalitz variable distributions extracted



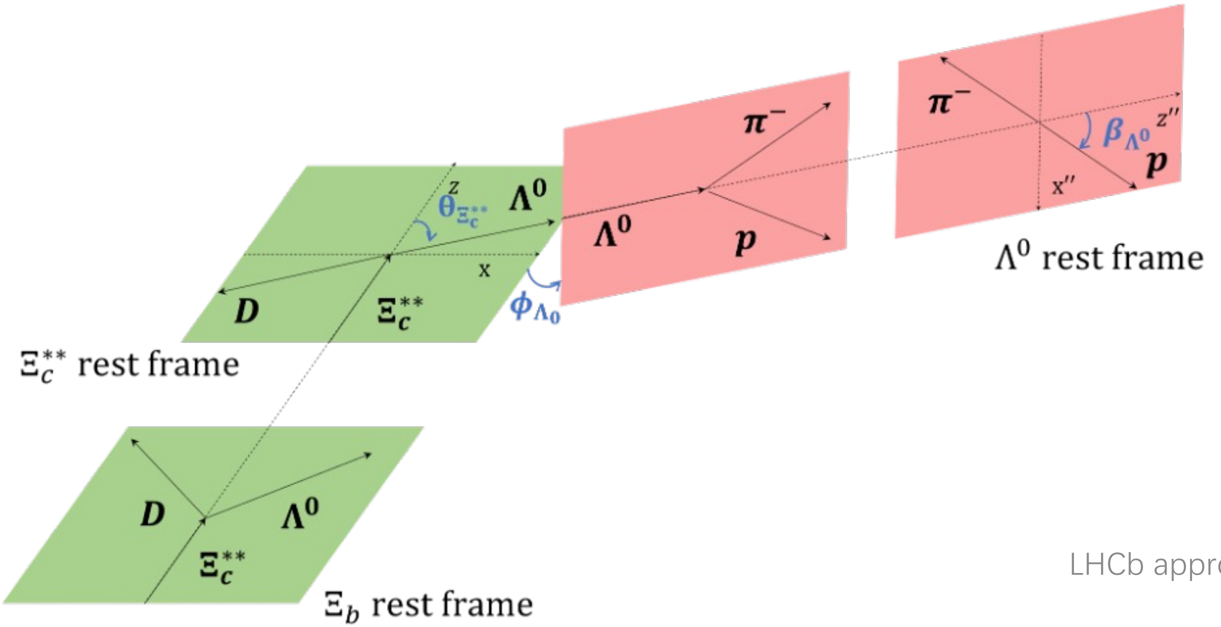


Helicity amplitude analysis

Helicity amplitude

➢ Helicity couplings in the $\Xi_b \to \Xi_c \pi,\ \Xi_c^{**} \to D\Lambda,\ \Lambda \to p\pi$ decay chain:

- $\Xi_b \to \Xi_c^{**}\pi^-$ $\quad A^{\Xi_b\to\Xi_c\pi^-}_{\lambda_{\Xi_b},\lambda_{\Xi_c},\lambda_\pi} = H^{\Xi_b\to\Xi_c\pi^-}_{\lambda_{\Xi_c}}\delta_{\lambda_{\Xi_b},\lambda_{\Xi_c}}$ — Floated for each resonance
- $\Xi_c^{**} \to D\Lambda$ $\quad A^{\Xi_c\to D\Lambda}_{\lambda_{\Xi_c},\lambda_D,\lambda_\Lambda} = H^{\Xi_c\to D\Lambda}_{\lambda_\Lambda} d^{J_{\Xi_c}}_{\lambda_{\Xi_c},\lambda_\Lambda}(\theta)$ — Strong decay, only phase term: $\eta^{P_{\Xi_c}}(-1)^{J_{\Xi_c}+1/2}$
- $\Lambda \to p\pi^-$ $\quad A^{\Lambda\to p\pi^-}_{\lambda_\Lambda,\lambda_p,\lambda_\pi} = H^{\Lambda\to p\pi^-}_{\lambda_p} D^{j_\Lambda}_{\lambda_\Lambda,\lambda_p}(\phi,\beta,0)$ — Fixed from input



$$\alpha_{\Xi_b\to\Xi_c^{**}\pi} \equiv \frac{\left|H^{\Xi_b}_{\lambda_{\Xi_c}=+\frac{1}{2}}\right|^2 - \left|H^{\Xi_b}_{\lambda_{\Xi_c}=-\frac{1}{2}}\right|^2}{\left|H^{\Xi_b}_{\lambda_{\Xi_c}=+\frac{1}{2}}\right|^2 + \left|H^{\Xi_b}_{\lambda_{\Xi_c}=-\frac{1}{2}}\right|^2}$$

LHCb approval

Amplitude model

- Coherent and incoherent sum:

$$f\left(m_{D\Lambda},\vec{\Omega};\vec{v}\right)=|M|^2=\sum_{\lambda_{\Xi_b},\lambda_p}\left|\sum_{\lambda_{\Xi_c},\lambda_\Lambda}A_{\Xi_c^{**}(3055)}+\sum_{\lambda_{\Xi_c},\lambda_\Lambda}A_{\Xi_c^{**}(3080)}+\sum_{\lambda_{\Xi_c},\lambda_\Lambda}A_{Non-resonance}\right|^2$$

- Relativistic Breit-Wigner for $\Xi_c^{**}(3055)$ and $\Xi_c^{**}(3080)$:

$$R_{BW}\left(m_{D\Lambda}\middle|m_0,\Gamma_0,l_p,l_d\right)=B_{l_p}(p,p_0,d)\left(\frac{p}{m_{\Xi_b}}\right)^{l_p}BW\left(m_{D\Lambda}|m_0,\Gamma_0,l_d\right)B_{l_d}(q,q_0,d)\left(\frac{q}{m_0}\right)^{l_d}$$

- Exponential lineshape for non-resonance:

$$R_{NR}\left(m_{D\Lambda}|a_{slope}\right)=B_{l_p}(p,p_0,d)\left(\frac{p}{m_{\Xi_b}}\right)^{l_p}e^{-am_{D\Lambda}^2}B_{l_d}(q,q_0,d)\left(\frac{q}{m_0}\right)^{l_d}$$

Likelihood construction

- sFit likelihood:

$$\log \mathcal{L}(\vec{\nu}) = \frac{\sum_{i\in data} w_i}{\sum_{i\in data} w_i^2} \sum_{i\in data} w_i \times \log \left[\mathcal{P}(m_{D\Lambda}^i, \vec{\Omega}^i|\vec{\nu})\right],$$

where PDF is matrix element mode square:

$$\mathcal{P}(m_{D\Lambda}, \vec{\Omega}|\vec{\nu}) = \frac{1}{I(\vec{\nu})} \sum_{\lambda_{\Xi_b},\lambda_p} \left|\mathcal{M}(m_{D\Lambda}, \vec{\Omega}|\vec{\nu})\right|^2 \times \Phi(m_{D\Lambda}, \vec{\Omega})\epsilon(m_{D\Lambda}, \vec{\Omega}),$$

efficiency encoded with MC integral:

$$I(\vec{\nu}) \equiv \int \sum_{\lambda_{\Xi_b},\lambda_p} \left|\mathcal{M}(m_{D\Lambda}, \vec{\Omega}|^2\vec{\nu})\right| \Phi\epsilon(m_{D\Lambda}, \vec{\Omega})dm_{D\Lambda}d\vec{\Omega}$$

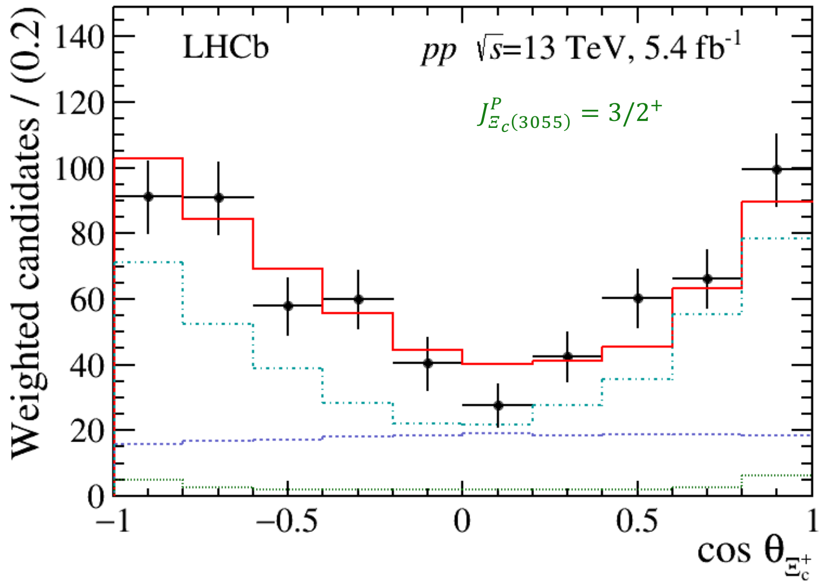
- Fit parameters $\vec{\nu}$:
  - helicity couplings of $\Xi_c^{**}(3055)$, $\Xi_c^{**}(3080)$, non-resonances
  - m_0, Γ_0 of $\Xi_c^{**}(3055)$
  - $J^P_{\Xi_c^{**}(3055)}$
- For each $J^P_{\Xi_c^{**}(3055)}$ hypotheses, minimized likelihood are compared

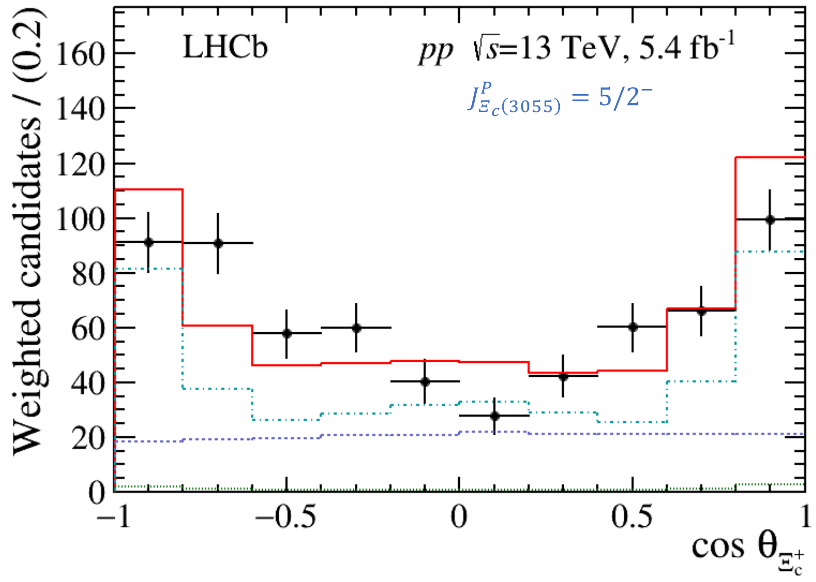
Hypotheses tests

- ➢ $J^P_{\Xi_c^{**}(3055)} = 3/2^+$ favored
  - among all tested hypotheses: $1/2^{\pm}, 3/2^{\pm}, 5/2^{\pm}, 7/2^{\pm}$
  - with rejection significance $n_\sigma \geq 6.5\sigma$ (from toy study)

	$J^P_{\Xi_c(3055)^+}$	$\alpha_{\Xi_b^0 \to \Xi_c(3055)^+\pi^-}$	n_σ
Favored	$\mathbf{3/2^+}$	$\mathbf{-0.92 \pm 0.10}$	-
	$1/2^-$	-0.10 ± 0.17	12.9σ
	$1/2^+$	$+0.31 \pm 0.13$	11.0σ
	$3/2^-$	$+0.18 \pm 0.14$	7.3σ
	$5/2^-$	-0.12 ± 0.14	6.5σ
	$5/2^+$	$+0.52 \pm 0.14$	9.8σ
	$7/2^-$	$+0.41 \pm 0.16$	10.7σ
	$7/2^+$	$+0.12 \pm 0.14$	10.9σ

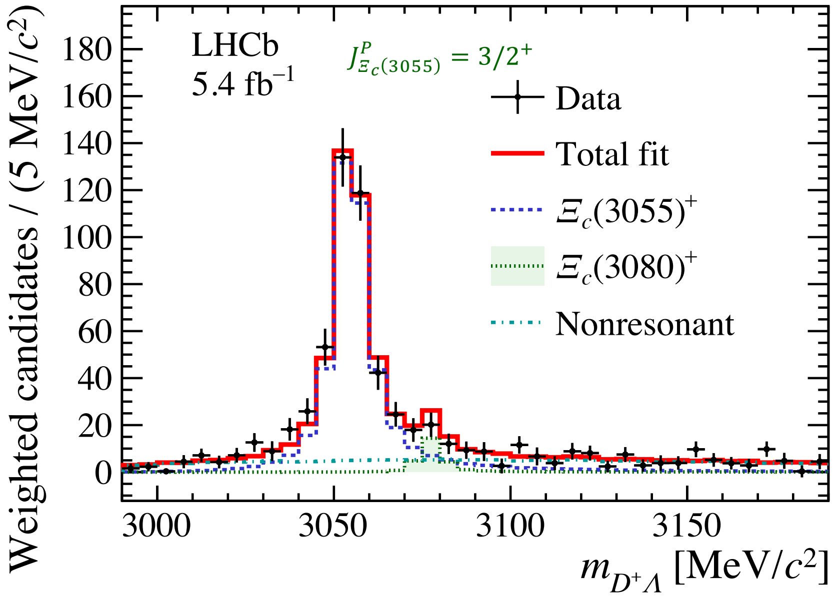
Projections to $\cos\theta$ for different hypothesized fits:

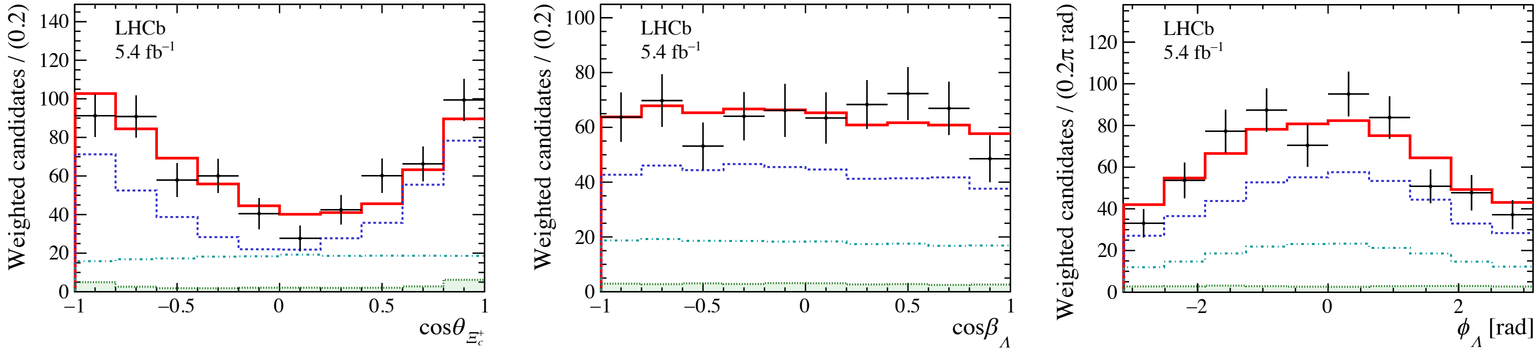




Run2, $\Xi_b^0 \to \Xi_c^{**+}\pi^-$ channel

Best fit projections: $J^P_{\Xi_c^{**}(3055)} = 3/2^+$





- $J^P_{\Xi_c^{**}(3055)} = 3/2^+, J^P_{\Xi_c^{**}(3080)} = 5/2^+, J^P_{NR} = 1/2^-$ (S-wave) as default

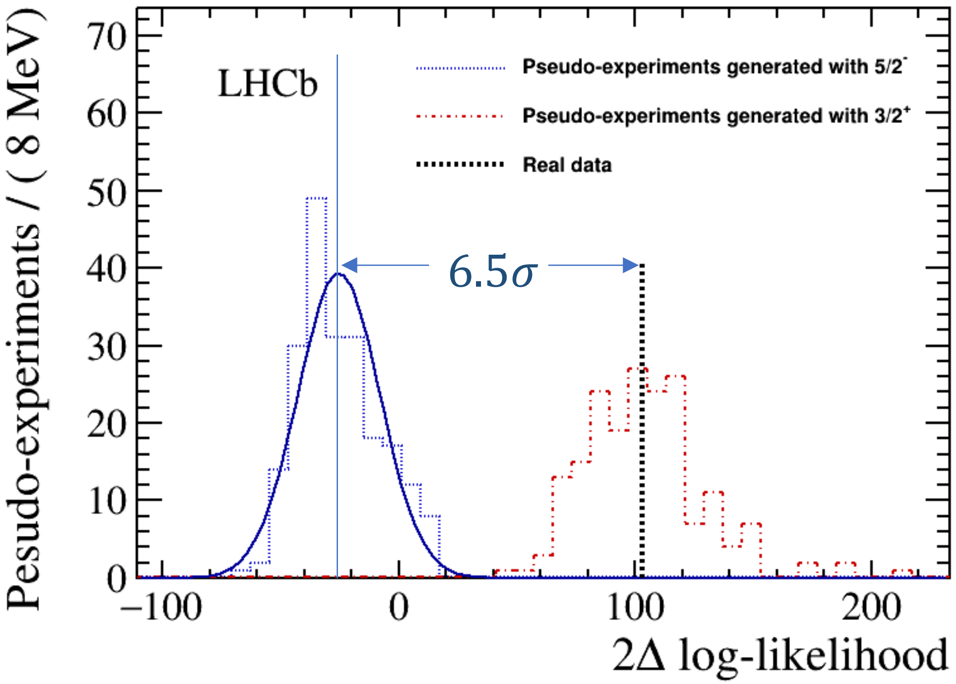
Table 1: Measured $\Xi_c^{**}(3055)$ properties

μ_0[MeV]	Γ_0[MeV]	$\alpha_{\Xi_b \to \Xi_c^{**}\pi}$
3054.52 ± 0.36	8.01 ± 0.76	-0.92 ± 0.10

PDG : $\mu_0 = 3055.9 \pm 0.4$ $\Gamma_0 = 7.8 \pm 1.9$

LHCb approval

Rejection significance



- Toys samples generated for alternative J^P hypotheses (J^P_{dis})
  - Parameters optimized
- Using test statistics:

$$t \equiv 2\ln\left[\mathcal{L}(J^P = 3/2^+)/\mathcal{L}(J^P_{\text{disfavor}})\right] = 2\Delta\log\mathcal{L}(3/2^+, \text{dis}),$$

- Significance rejecting J^P_{dis} is determined with:

$$n_\sigma(J_{\text{disfavor}}) = \frac{t_{\text{data}} - \mu(t_{J_{\text{disfavor}}})}{\sigma(t_{J_{\text{disfavor}}})},$$

$J^P_{\Xi_c(3055)^+}$	n_σ
$\mathbf{3/2^+}$	-
$1/2^-$	12.9σ
$1/2^+$	11.0σ
$3/2^-$	7.3σ
$5/2^-$	6.5σ
$5/2^+$	9.8σ
$7/2^-$	10.7σ
$7/2^+$	10.9σ

Systematic uncertainties

Systematics

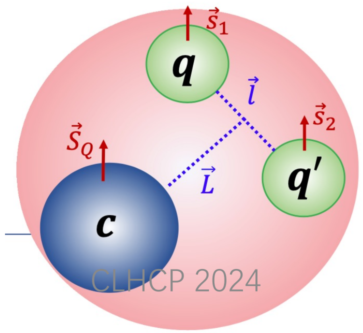
Table 3: Biases and systematic uncertainties for the $\Xi_b^0 \to \Xi_c(3055)^+\pi^-$ channel.

Source	σ_m [MeV/c^2]	σ_Γ [MeV/c^2]	σ_α	$\sigma_{R_\mathcal{B}}$
Amplitude fit bias	–	–	–	–
Hadron masses	±0.05	–	–	–
Momentum scale	±0.01	–	–	–
Resolution	±0.00	±0.07	±0.00	±0.000
Simulation sample	±0.15	±0.30	±0.02	±0.002
Trigger correction	±0.01	±0.03	±0.02	±0.000
Λ categories	±0.03	±0.04	±0.01	±0.002
Ξ_b^0 mass fit model	±0.03	±0.13	±0.01	±0.001
Angular momentum	±0.00	±0.00	±0.04	±0.002
Nonresonant model	±0.00	±0.00	±0.00	±0.000
$\Xi_c(3080)^+$ width	±0.01	±0.01	±0.00	±0.003
$\Xi_c(3080)^+$ mass	±0.00	±0.02	±0.00	±0.000
Clone tracks	±0.02	±0.03	±0.01	±0.003
Total	±0.17	±0.34	±0.05	±0.006

Summary

Theoretical interpretations of $\Xi_c(3055)$

References	Theoretical model	J^P of $\Xi_c(3055)$
Eur. Phys. J. A 37 (2008) 217–225	Faddeev method	$5/2^+$ (1D)
Phys. Rev. D 78 (2008) 056005	Regge phenomenology	$5/2^+$ (1D)
Phys. Rev. D 84 (2011) 014025	QCD-motivated relativistic quark model	$3/2^+$ (1D)
Phys. Rev. D 86 (2012) 034024	Chiral quark model	$3/2^+$ (1D)
Eur. Phys. J. A 82 (2015) 51	Relativistic flux tube model	$3/2^+$ (1D)
Phys. Rev. D 94 (2016) 114016	QCD sum rules within HQET	$3/2^+$ (1D)
Phys. Rev. D 96 (2017) 114003	3P0 model	$1/2^+(\bar{3}_F), 3/2^+(6_F)$ (2S)
Eur. Phys. J. C 79 (2019)167	Hadron molecular state	$1/2^-, 3/2^-$ (molecular)



Summarized in Rept.Prog.Phys. 80 (2017) no.7, 076201

Or see our paper draft

Decay parameter

$$\alpha_{\Xi_b \to \Xi_c^{**}\pi} \equiv \frac{\left|H^{\Xi_b}_{\lambda_{\Xi_b}=+}\right|^2 - \left|H^{\Xi_b}_{\lambda_{\Xi_b}=-}\right|^2}{\left|H^{\Xi_b}_{\lambda_{\Xi_b}=+}\right|^2 + \left|H^{\Xi_b}_{\lambda_{\Xi_b}=-}\right|^2}$$

- Our measurement: $\alpha_{\Xi_b \to \Xi_c(3055)^+\pi}$ $-0.92 \pm 0.10 \pm 0.05$
- Calculations for similar decay modes $\approx -100\%$
  - $\bar{3}_F \to \bar{3}_F$ beauty to charm transitions
  - pure parity violation
- Only consistent with our measurement under hypothesis $J^P = 3/2^+$

TABLE XIV: The predicted up-down asymmetries of $\mathcal{B}_b \to \mathcal{B}_c P$ decays. The asymmetries are given in unit of %. The asterisks in the first column indicate that the baryons in the final states are radial excited.

Unit : %

Type	Mode	$P=\pi^-$	$P=K^-$	$P=D^-$	$P=D_s^-$
(i)	$\alpha(\Lambda_b \to \Lambda_c P)$	$-99.99^{+2.24}_{-0.00}$	$-99.98^{+2.41}_{-0.00}$	$-98.47^{+8.91}_{-1.52}$	$-98.06^{+9.41}_{-1.87}$
(i)	$\alpha(\Xi_b^0 \to \Xi_c^+ P)$	$-99.99^{+2.24}_{-0.00}$	$-99.97^{+2.41}_{-0.00}$	$-98.40^{+9.01}_{-1.59}$	$-97.96^{+9.52}_{-1.96}$
(i)	$\alpha(\Xi_b^- \to \Xi_c^0 P)$	$-99.99^{+2.24}_{-0.00}$	$-99.97^{+2.41}_{-0.00}$	$-98.39^{+9.01}_{-1.59}$	$-97.96^{+9.53}_{-1.96}$
(i)*	$\alpha[\Lambda_b \to \Lambda_c(2765)P]$	$-100.00^{+2.14}_{-0.00}$	$-99.98^{+2.39}_{-0.00}$	$-96.61^{+10.76}_{-3.32}$	$-95.54^{+11.49}_{-4.46}$
(ii)	$\alpha(\Omega_b \to \Omega_c P)$	$59.92^{+9.88}_{-9.22}$	$59.93^{+9.88}_{-9.22}$	$59.95^{+14.95}_{-13.54}$	$59.90^{+14.95}_{-13.53}$
(ii)*	$\alpha[\Omega_b \to \Omega_c(3090)P]$	$60.02^{+9.88}_{-9.23}$	$60.02^{+9.88}_{-9.23}$	$59.49^{+14.93}_{-13.47}$	$59.23^{+14.92}_{-13.43}$
(iii)	$\alpha[\Lambda_b \to \Lambda_c(2595)P]$	$-98.86^{+4.77}_{-1.04}$	$-98.84^{+4.79}_{-1.05}$	$-97.86^{+9.63}_{-2.03}$	$-97.57^{+9.93}_{-2.25}$
(iii)	$\alpha[\Xi_b^0 \to \Xi_c^+(2790)P]$	$-99.13^{+4.44}_{-0.84}$	$-99.12^{+4.44}_{-0.84}$	$-98.58^{+8.77}_{-1.42}$	$-98.39^{+9.02}_{-1.59}$
(iii)	$\alpha[\Xi_b^- \to \Xi_c^0(2790)P]$	$-99.13^{+4.44}_{-0.84}$	$-99.12^{+4.44}_{-0.84}$	$-98.58^{+8.76}_{-1.42}$	$-98.39^{+9.02}_{-1.59}$
(iii)*	$\alpha[\Lambda_b \to \Lambda_c(2940)P]$	$-98.86^{+4.76}_{-1.03}$	$-98.84^{+4.78}_{-1.05}$	$-97.04^{+10.41}_{-2.81}$	$-96.36^{+10.94}_{-3.60}$

Ref:1811.09265

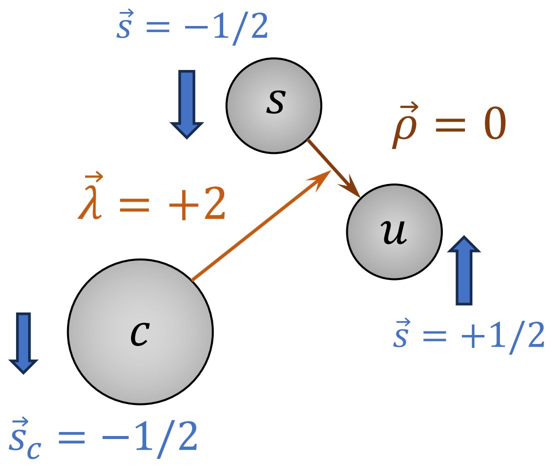
Conclusion

The $\Xi_b^0 \to D^+\Lambda^0\pi^-$ and $\Xi_b^- \to D^0\Lambda^0\pi^-$ decays are observed for the first time:

- $\Xi_c(3055)^{+(0)}$ mass and width are measured
- $\Xi_c(3055)^{+(0)}$ spin-parity measured to be $3/2^+$
  - With significance of $6.5(3.5)\sigma$
  - First determination with significance over 5σ of a charm-strange baryons
- Decay parameter in $\Xi_b^{0(-)} \to \Xi_c(3055)^{+(0)}\pi^-$ measured to be:

$$-0.92 \pm 0.10 \pm 0.05(-0.92 \pm 0.16 \pm 0.22)$$

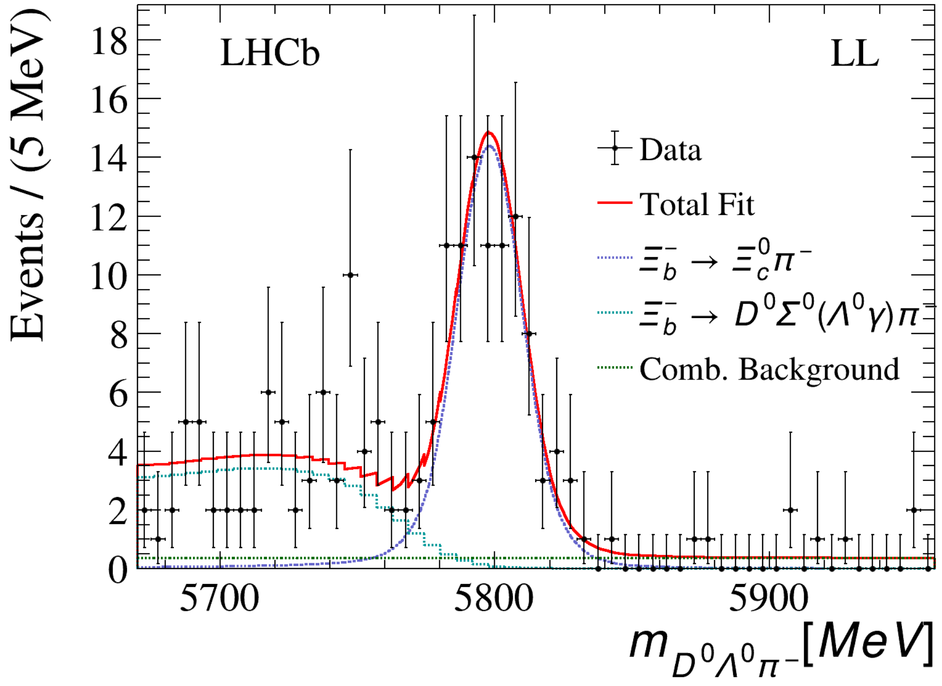
  - First time in beauty to charm + pseudoscalar decays
- Consistent with first D-wave, λ-mode excitation of $\overline{3}_F$ category

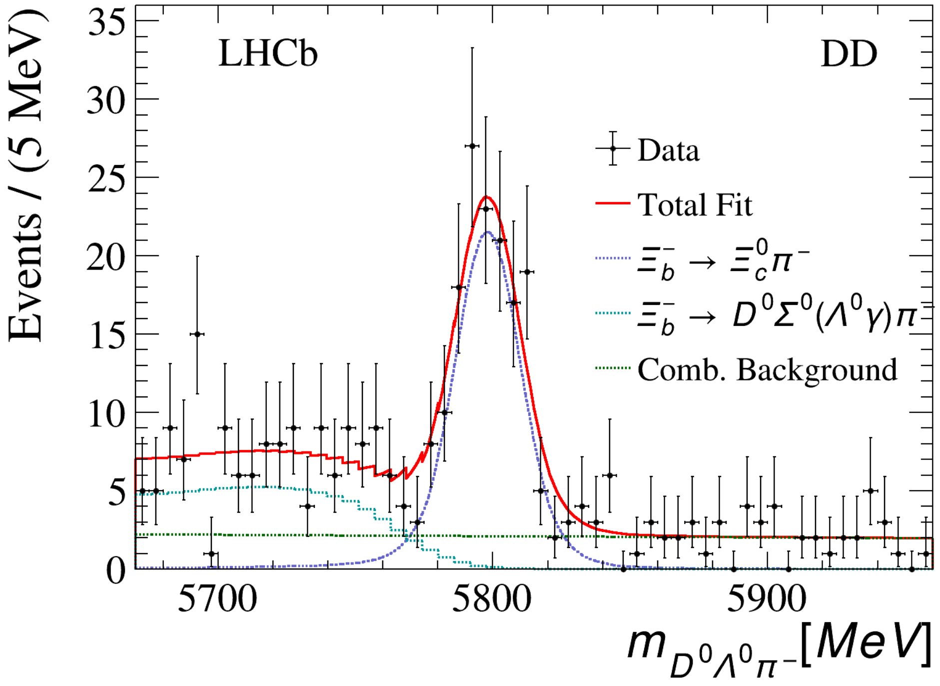


Thanks for your attention!

$\Xi_b^- \to \Xi_c^{**0}\pi^-$ channel results

Ξ_b mass fit



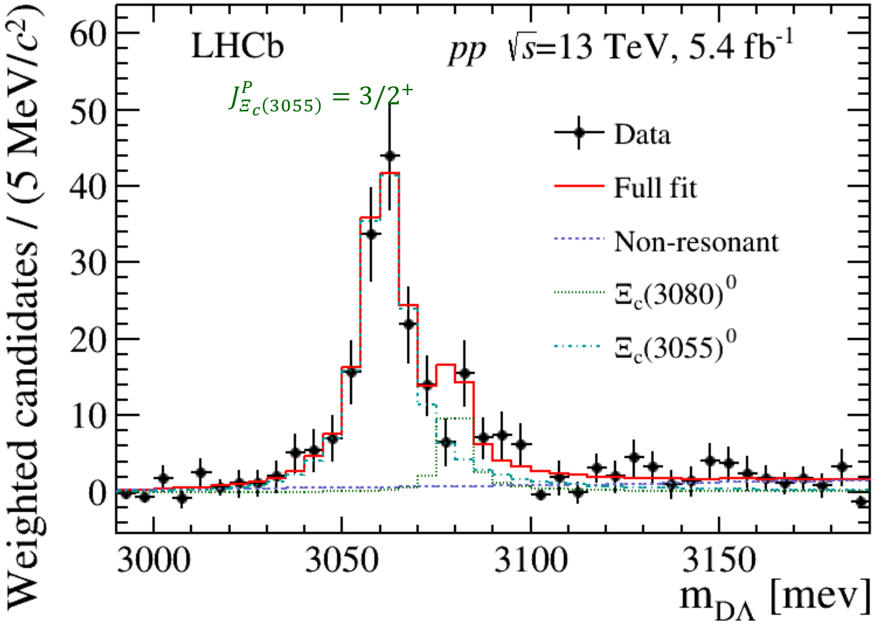


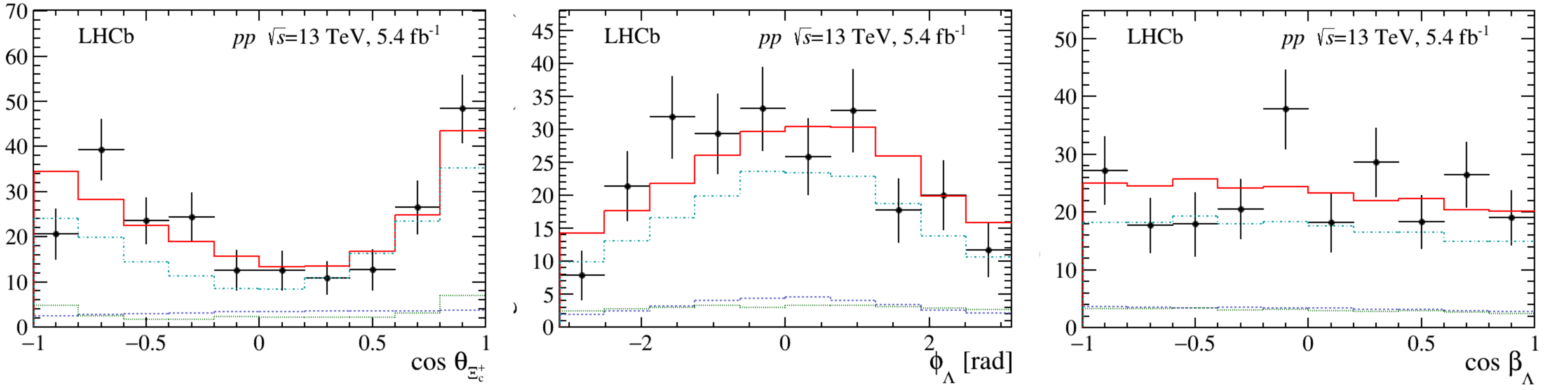
- Signal model: Gaussian + DSCB (parameters determined from MC)
- Partial reconstruction: shape from fast simulation
- Combinatorial background: exponential

➢ Simultaneously for LL & DD

Parameters	Fit Result(DD)	Fit Result(LL)
$\mu_{\Xi_b^-}$	5798.2±1.0 MeV	
$\sigma_{\Xi_b^-}$	12.5±1.0 MeV	
signal yield	139±16	93±10

Best fit projections: $J^P_{\Xi_c^{**}(3055)} = 3/2^+$





JP hypotheses	significance
$3/2+$	-
$1/2-$	5.5σ
$1/2+$	6.5σ
$3/2-$	3.5σ
$5/2-$	4.8σ
$5/2+$	4.8σ
$7/2-$	6.0σ
$7/2+$	6.2σ

Table 1: Measured $\Xi_c^{**}(3055)$ properties

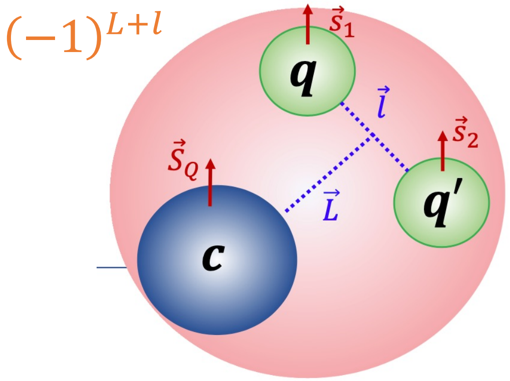
μ_0[MeV]	Γ_0[MeV]	$\alpha_{\Xi_b \to \Xi_c^{**}\pi}$
3061.00 ± 0.80	12.4 ± 2.0	-0.92 ± 0.16

Systematics

Table 4: Biases and systematic uncertainties for the $\Xi_b^- \to \Xi_c(3055)^0\pi^-$ channel.

Source	σ_m[MeV/c^2]	σ_Γ[MeV/c^2]	σ_α	$\sigma_{R_\mathcal{B}}$
Amplitude fit bias	–	−0.46	–	–
Hadron masses	±0.05	–	–	–
Momentum scale	±0.03	–	–	–
Resolution	±0.00	±0.10	±0.00	±0.001
Simulation sample	±0.13	±0.38	±0.02	±0.006
Trigger correction	±0.01	±0.03	±0.00	±0.001
Λ categories	±0.04	±0.12	±0.05	±0.004
Ξ_b^- mass fit model	±0.00	±0.19	±0.02	±0.003
Angular momentum	±0.01	±0.15	±0.21	±0.014
Nonresonant model	±0.00	±0.03	±0.00	±0.001
$\Xi_c(3080)^0$ width	±0.08	±0.69	±0.01	±0.032
$\Xi_c(3080)^0$ mass	±0.03	±0.20	±0.01	±0.006
Clone tracks	±0.13	±0.04	±0.04	±0.008
Total	±0.23	±1.11	±0.22	±0.038

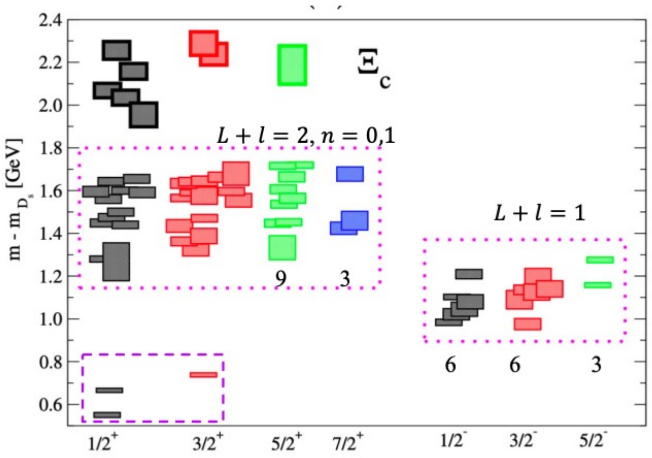
Decay Parameter

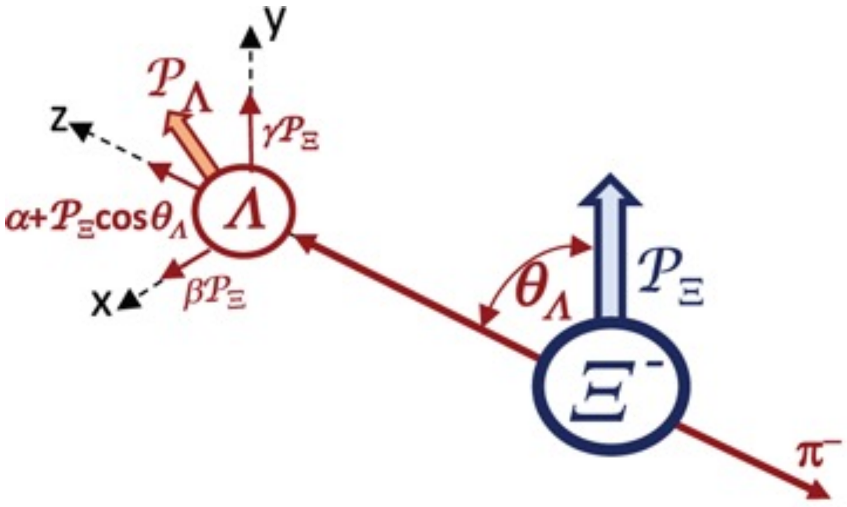


- **Decay parameter:**

$$\alpha = \frac{2|S||P|cos(\delta \pm \phi)}{|S|^2 + |P|^2}$$

- Relative transition possibility between up & down parity



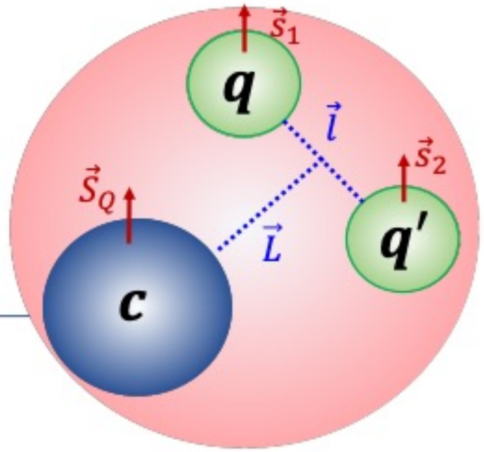


(a)

Orbital angular momenta

ρ modes: $l \neq 0$
λ modes: $L \neq 0$

Can happen at the same time



For only λ modes

1P Negative parity

$(S_l, \quad J)$

There are two P-wave states for $\Xi_c(0, 1/2)$ $1/2^-$ and $3/2^-$
another two P-wave states for $\Xi'_c(1, 1/2)$ $1/2^-$ and $3/2^-$,
and another three P-wave states for $\Xi^*_c(1, 3/2)$ $1/2^-$, $3/2^-$ and $5/2^-$.

7 in total

2D positive parity

There are two D-wave states for $\Xi_c(0, 1/2)$ $3/2^+$ and $5/2^+$,
another two D-wave states for $\Xi'_c(1, 1/2)$ $3/2^+$ and $5/2^+$,
and another four D-wave states for $\Xi^*_c(1, 3/2)$ $1/2^+$, $3/2^+$, $5/2^+$ and $7/2^+$.

8 in total

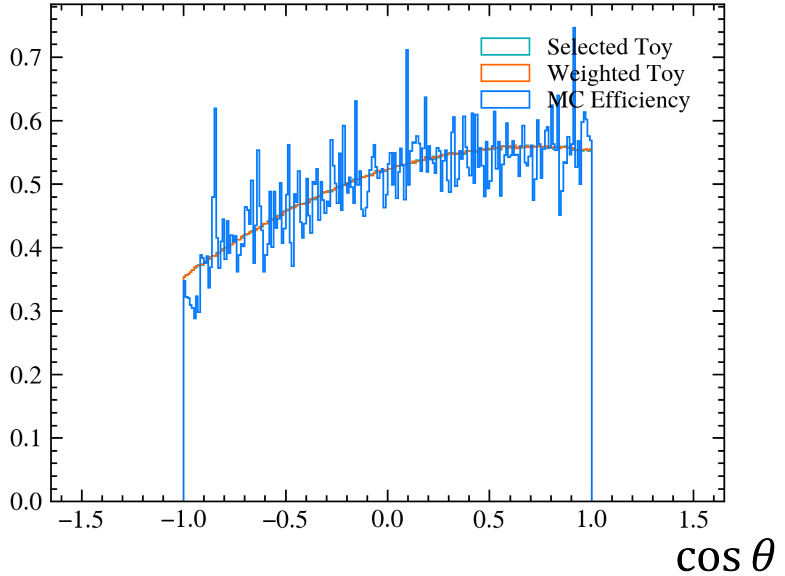
$S: 0$
$P: 1$
$D: 2$
$F: 3$

Backup

Toy study

1. Construct model $f\left(m_{D\Lambda}, \vec{\Omega}; \vec{v}', J^P_{dis}\right)$ for disfavored $J^P_{dis} = 1/2^{\pm}, 3/2^{-}, 5/2^{\pm}, 7/2^{\pm}$
   - Parameters $\vec{v}'$ are optimized from hypothesized fit
2. Sampling component from PDF=$f\left(m_{D\Lambda\pi}; \vec{v}_{\Xi_b}\right) \times \epsilon_i(m_{D\Lambda\pi}) \times f\left(m_{D\Lambda}, \vec{\Omega}; \vec{v}_{\Xi_c}', J^P_{dis}\right) \times \epsilon_i(m_{D\Lambda}, \vec{\Omega})$
   - Variable space: $m_{D\Lambda\pi}$, $m_{D\Lambda}$, $\vec{\Omega}(\cos\theta, \cos\beta, \phi)$
   - Poisson randomized entries
   - Efficiency from MC (Legendre expansion)
3. sFit with disfavored model (J^P_{dis}), and favored model ($J^P_{fav} = 3/2^{+}$)

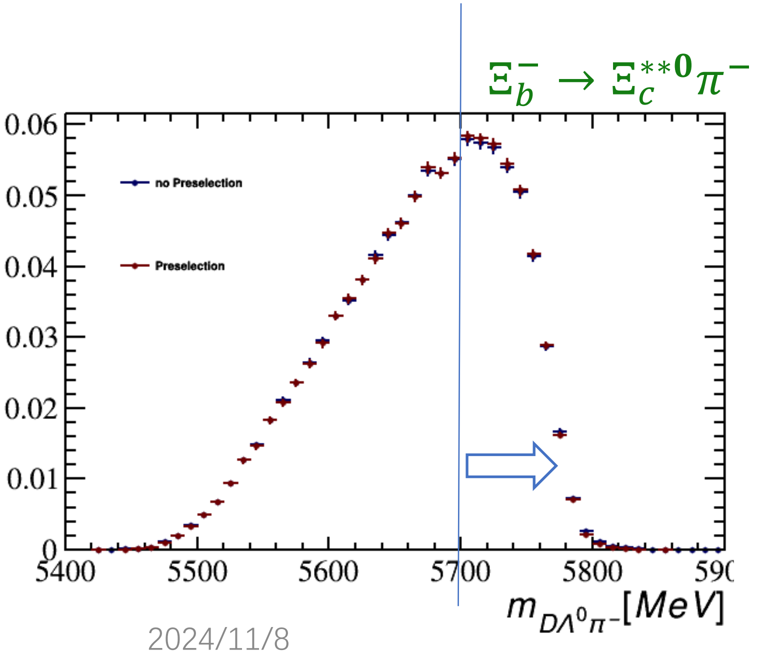
Fig 1: MC efficiency expansion of $\cos\theta$

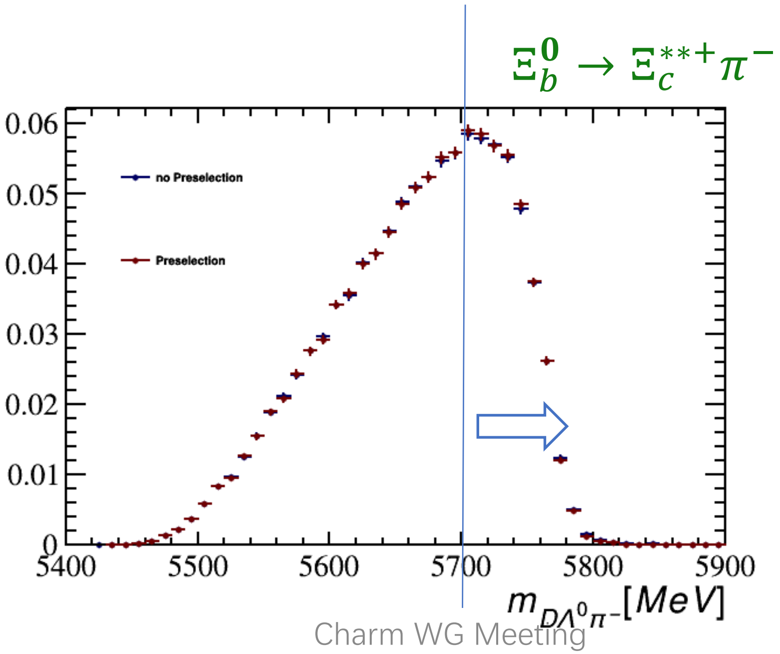


LHCb approval

Components : partial reconstruction

- $\Xi_b \to D\Sigma^0(\to \Lambda^0\gamma)\pi^-$ samples generated with RapidSim , invariant mass of $D\Lambda^0\pi^-$ (Ξ_b with a γ lost) calculated
- Influence of preselection neglectable





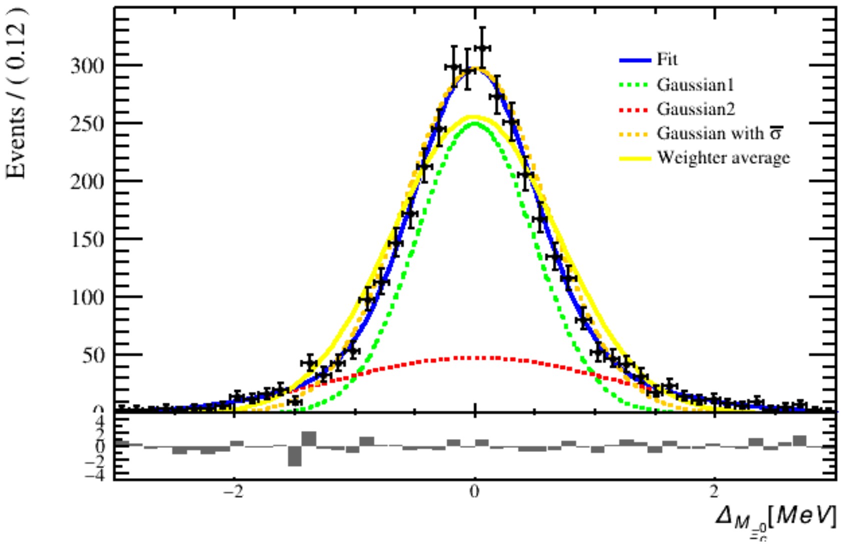
Particles	Preselection
π	$ProbNNpi > 0.1$
K	$ProbNNk > 0.2$
$m(\Lambda)$	$PDG\ value \pm$ 6MeV
$m(\Xi_b)$	$PDG\ value \pm$ 700MeV
$m(D)$	$PDG\ value \pm$ 20MeV

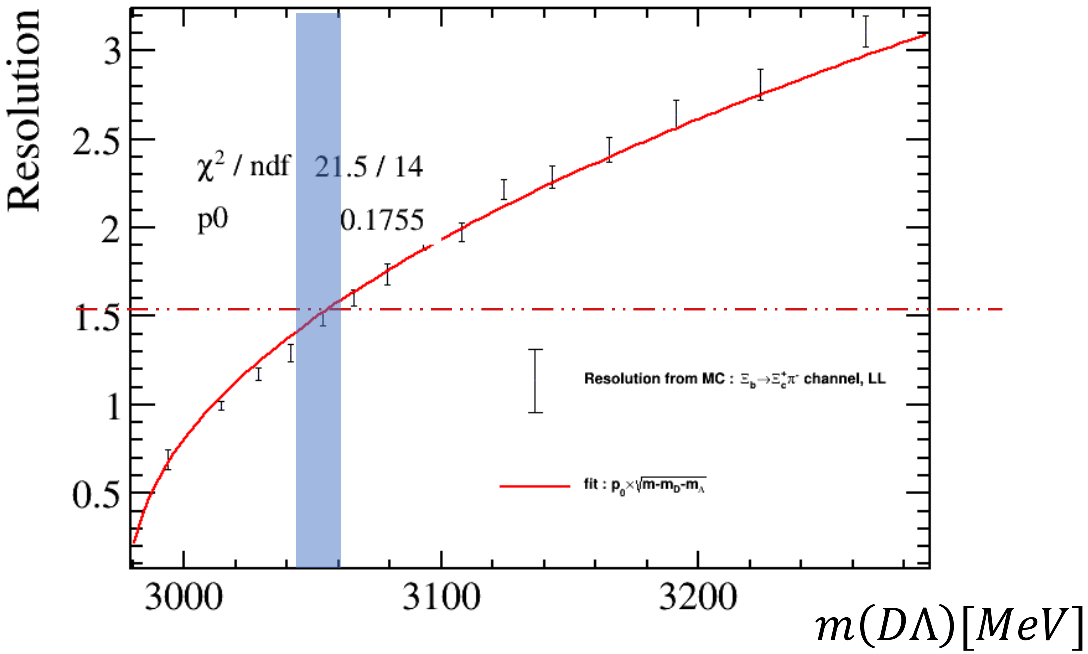
Resolution

- Resolution of Ξ_c^{**} evaluated with MC samples :
  - Fit $(M_{True} - M_{Reconstruction})$ in each m(DΛ) bin with :

$$f \times Gaussian_1 + (1-f) Gaussian_2$$

  - Choose constant width 1.3MeV
  - Convolute to PDF

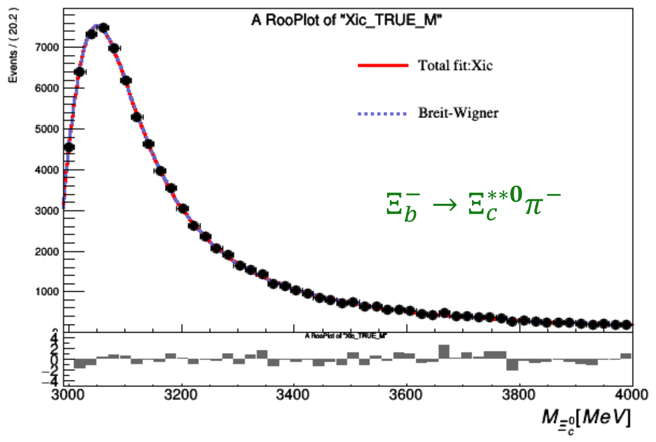


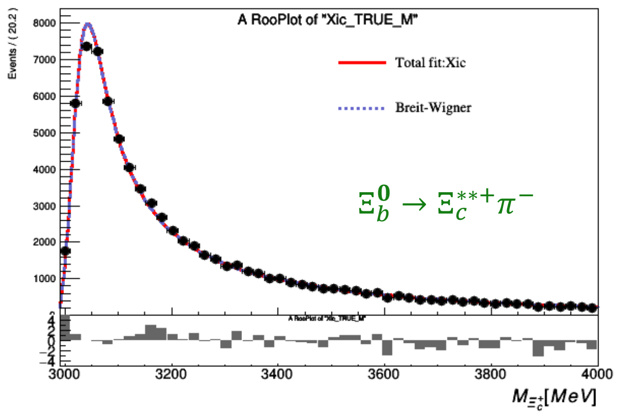


MC distribution reweighting

The simulated Ξ_c^{**} in MC were modified from $\Xi_c^{\sim}(2815)$ and $\Xi_c^{+}(2790)$, (D^0/D^+ channels , respectively) with different mean values and large widths.

In correction of $\mathrm{m}(D\Lambda)$ distribution, MC samples were reweighted to BW distribution from data fit results



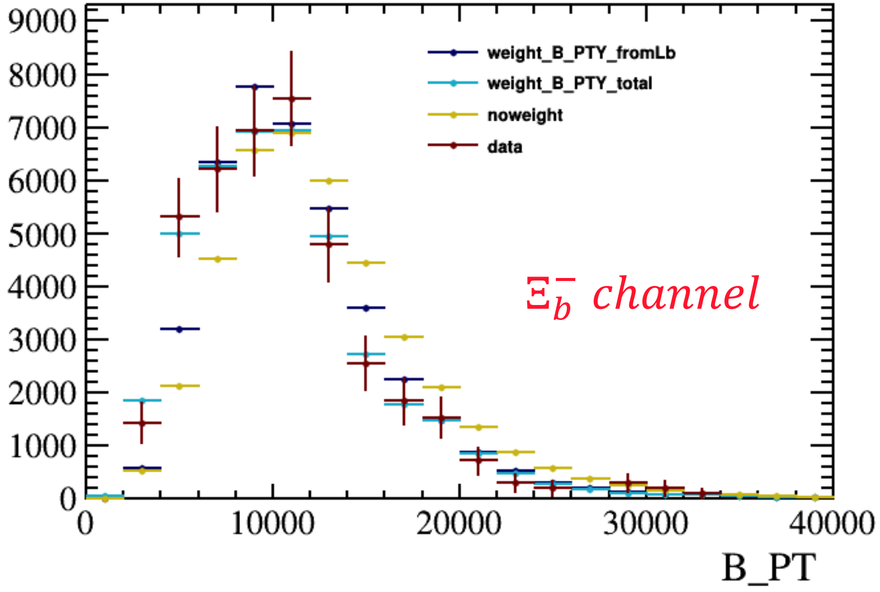


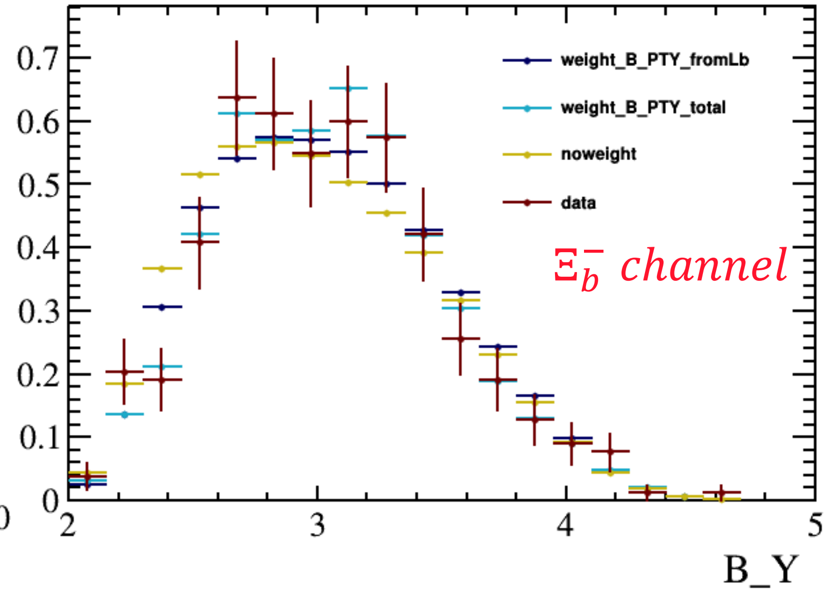
	Parameters	Input value (in decfile)	Observed value (fit result)
(Ξ_c^+)	M_0	3077.2	3055.0
	Γ_0	223	8.5
(Ξ_c^0)	M_0	3079.9	3062.2
	Γ_0	223	11.2

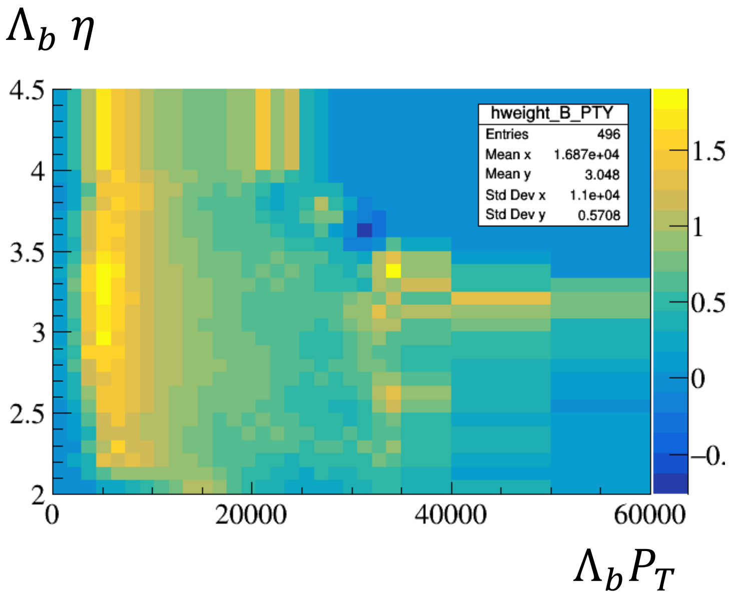
[MeV]

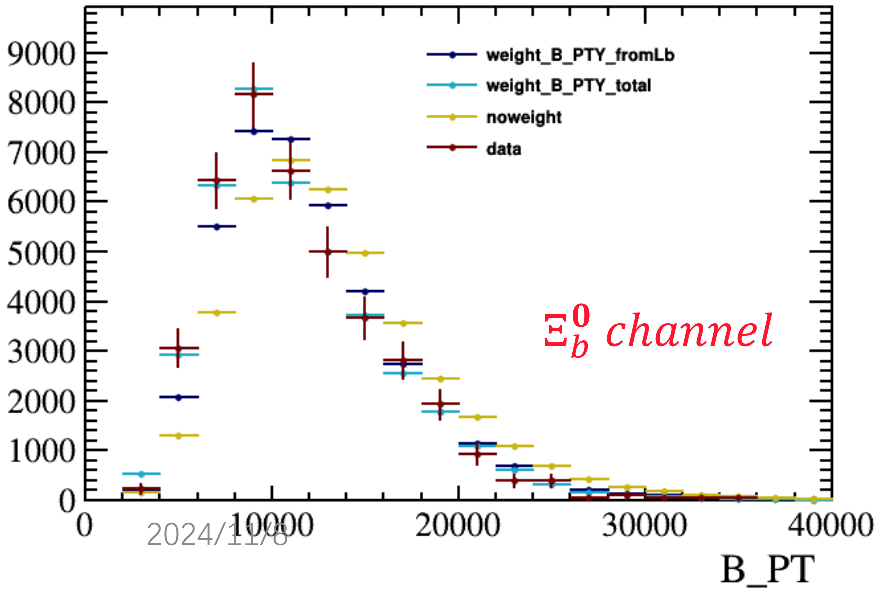
$\Xi_c^{**+}(2790)$ has spin 3/2 in simulation (with orbital angular momentum $l = 1$ in its decay to $D^+\Lambda^0$)

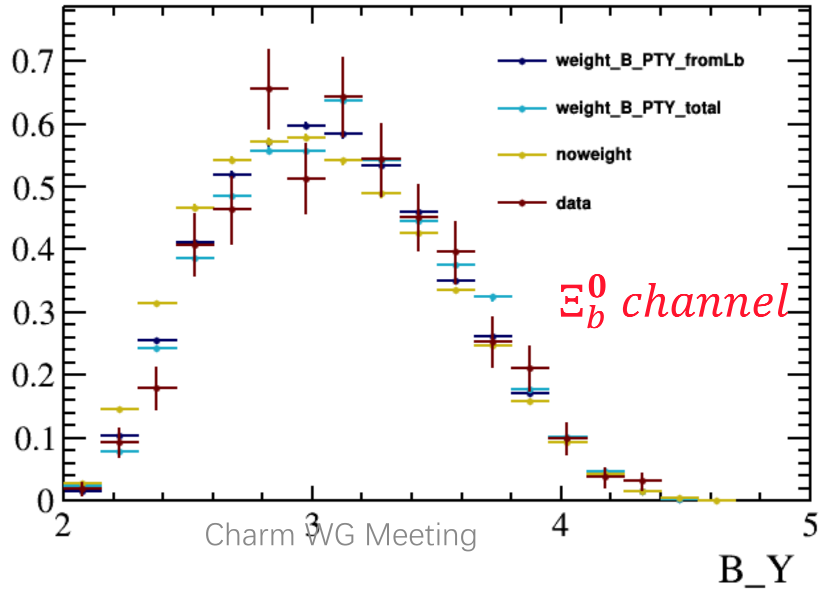
MC correction : PT_Y reweighting







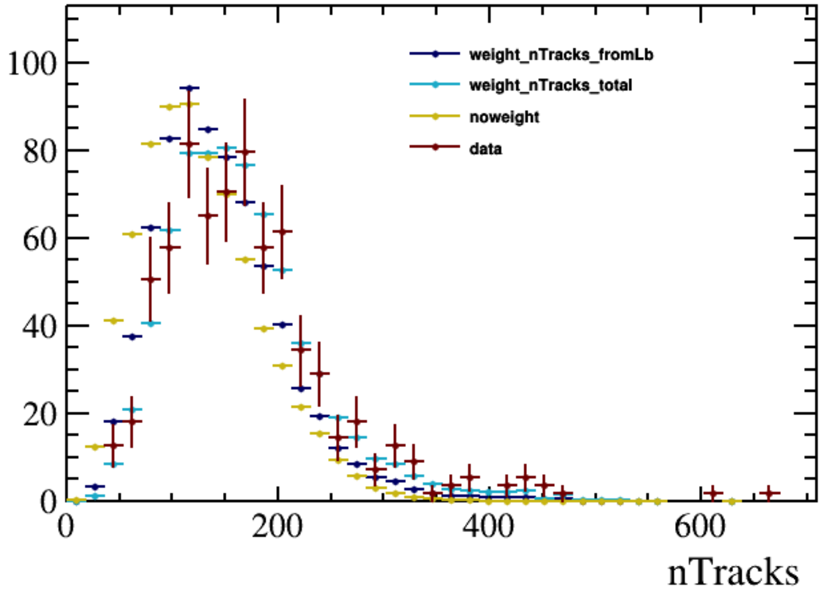




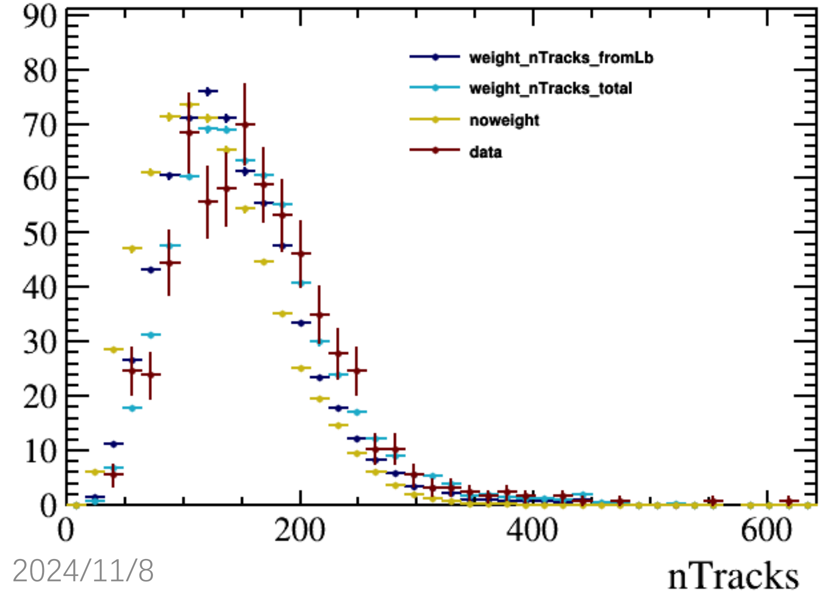
A first step weights obtained from Λ_b were used.

Then a second weight calculate from our own data distributions were applied.

MC correction : nTracks reweighting

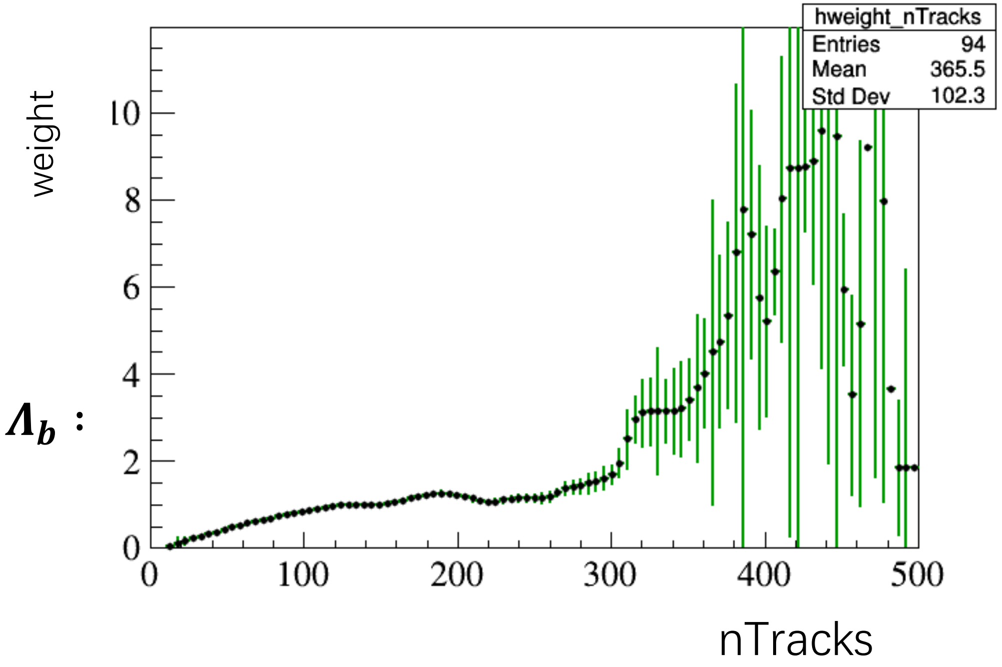


Ξ_b^- *channel*

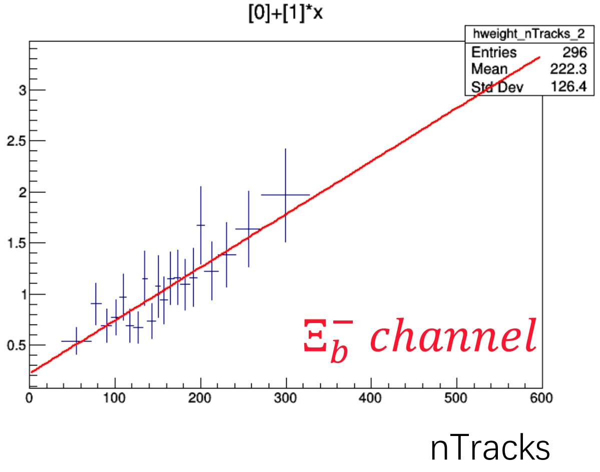


Ξ_b^0 *channel*

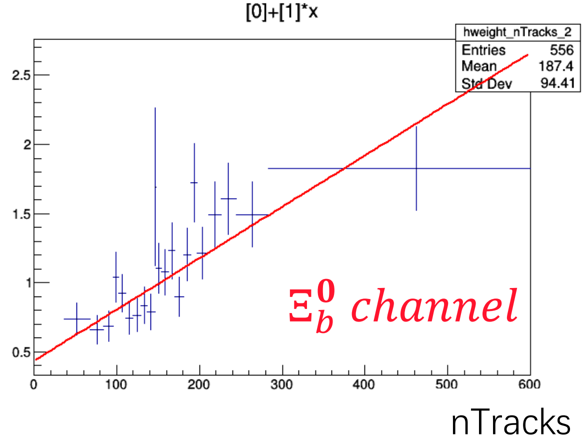
From Λ_b :



Own data:



Ξ_b^- *channel*



Ξ_b^0 *channel*

Trigger Efficiency

- MC errors in L0 trigger efficiency for :
  - TIS : $L0\_Photon|Electron|Muon|DiMuon\_TIS$

    Calibrated using TISTOS method

  - TOS : $L0\_Hadron\_TOS$

    Calibrated using E_T dependent data driven L0 efficiency for each trach

TIS Efficiency Calibration

- TIS efficiency as a function of Ξ_b transverse momentum:

$$\epsilon_{TIS} = \frac{N_{TIS\&TOS}(p_T)}{N_{TOS}(p_T)}$$

- Evaluated for data and MC in each p_T bins

- MC corrected according to differences

➢ Data efficiency is evaluated with $\Xi_b \to \Xi_c \pi^-$ decay, with larger statistics

TIS Efficiency : Efficiency distributions

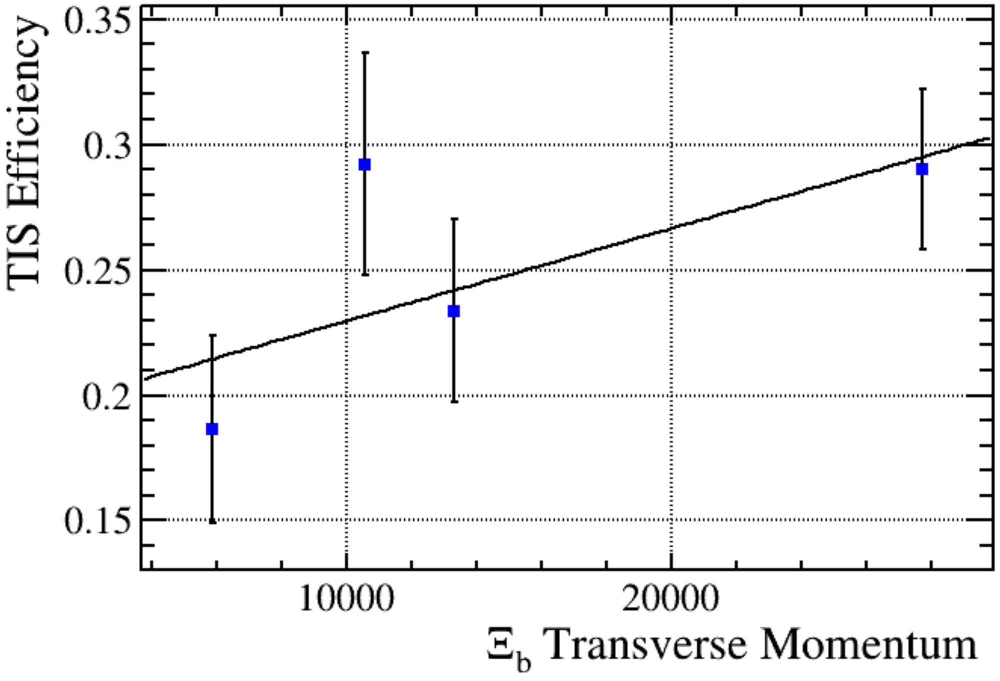


Fig.1 Data efficiency taken from
$\Xi_b \to \Xi_c \pi^-$ ground state decay

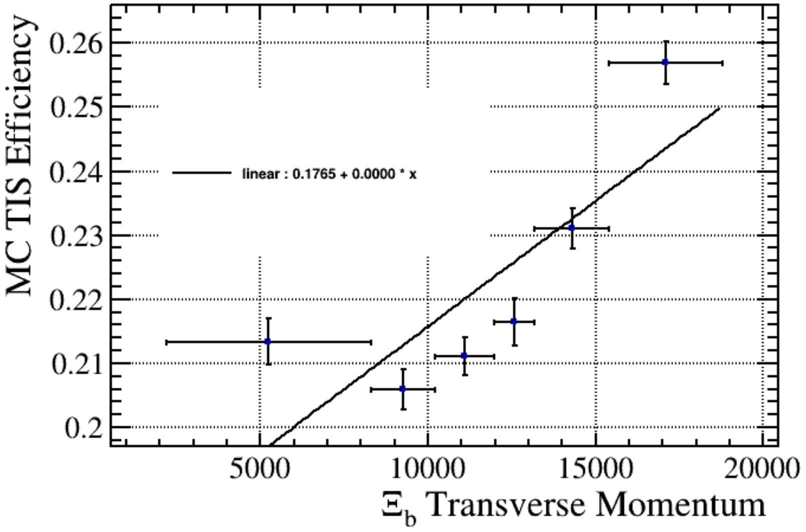


Fig.2 $\Xi_b^- \to \Xi_c^{**0}\pi^-$ channel

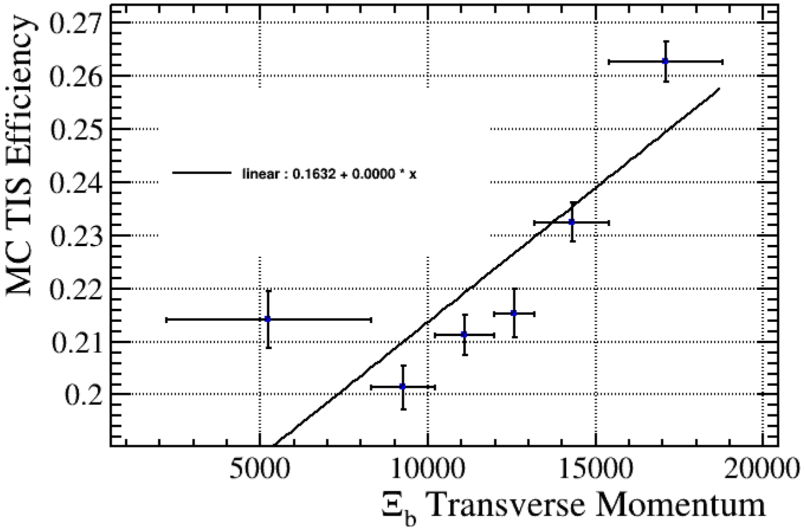


Fig.3 $\Xi_b^0 \to \Xi_c^{**+}\pi^-$ channel

TOS Efficiency Calibration

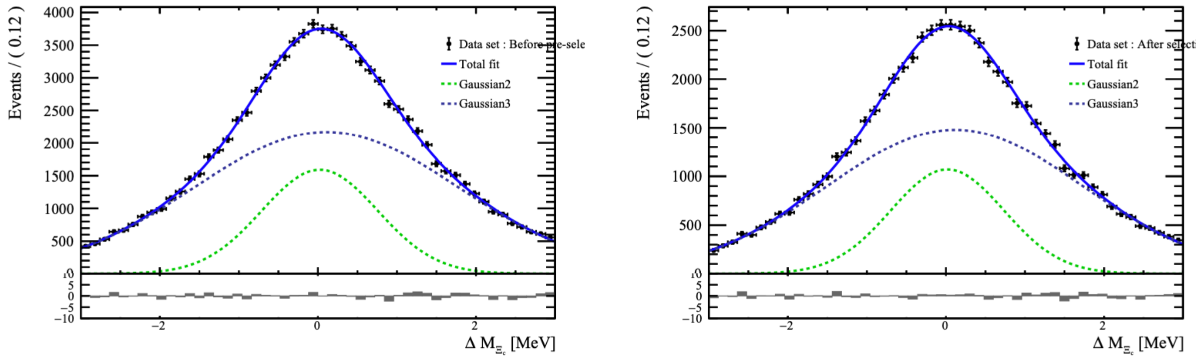
- L0 TOS efficiency is tabulated with respect to E_T of final tracks
- Fitting variables distribution in two MC samples are compared:
  - Cut with L0_Hadron_TOS decision
  - Weighted with L0 efficiency table
- The first sample is calibrated to the second sample
  - With GBReweighter method
  - Concerning fitting variables $m(D\Lambda)$, $\cos\theta$, $\cos\beta$ and α
- Events triggered with TIS/TOS are separately weighted

Selection Bias

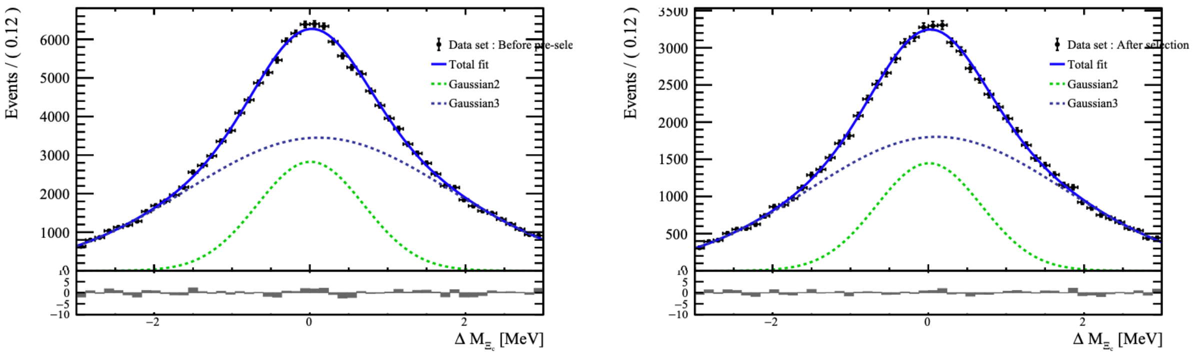
- Effects of Pre-selection & MVA :
  - Evaluated with MC
  - Distribution of $\Delta M = M_{\text{reconstruction},\Xi_c} - M_{\text{true},\Xi_c}$ is fitted
  - μ evaluated for samples before and after selection
  - $\Delta\mu$ taken as bias, all within $\pm 0.001 MeV$

Dataset	$\mu_1[\text{MeV}/c^2]$	$\mu_2[\text{MeV}/c^2]$	Correlation	$\Delta\mu[\text{MeV}/c^2]$
$\Xi_b^0 \to D^+\Lambda\pi^-$, DD	0.067 ± 0.007	0.065 ± 0.006	0.81	-0.001 ± 0.004
$\Xi_b^0 \to D^+\Lambda\pi^-$, LL	0.064 ± 0.012	0.064 ± 0.011	0.79	0.000 ± 0.007
$\Xi_b^- \to D^0\Lambda\pi^-$, DD	0.059 ± 0.006	0.059 ± 0.006	0.71	0.000 ± 0.003
$\Xi_b^- \to D^0\Lambda\pi^-$, LL	0.063 ± 0.007	0.064 ± 0.006	0.84	0.001 ± 0.003

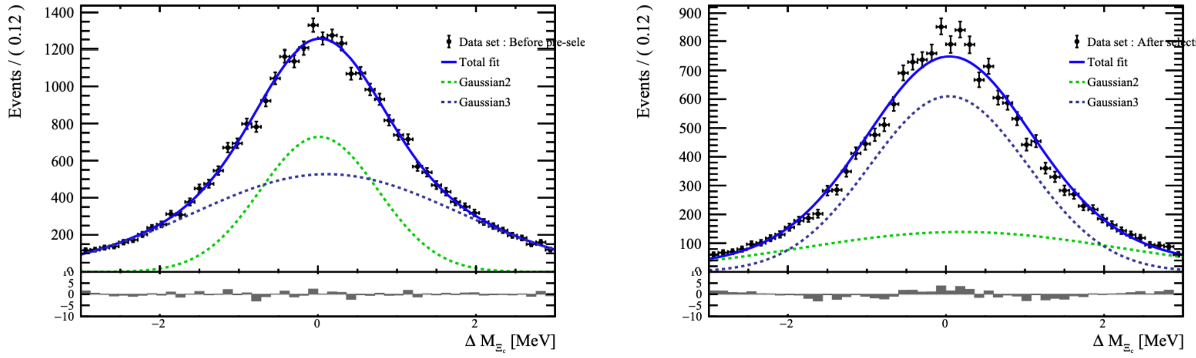
Selection Bias : Figures



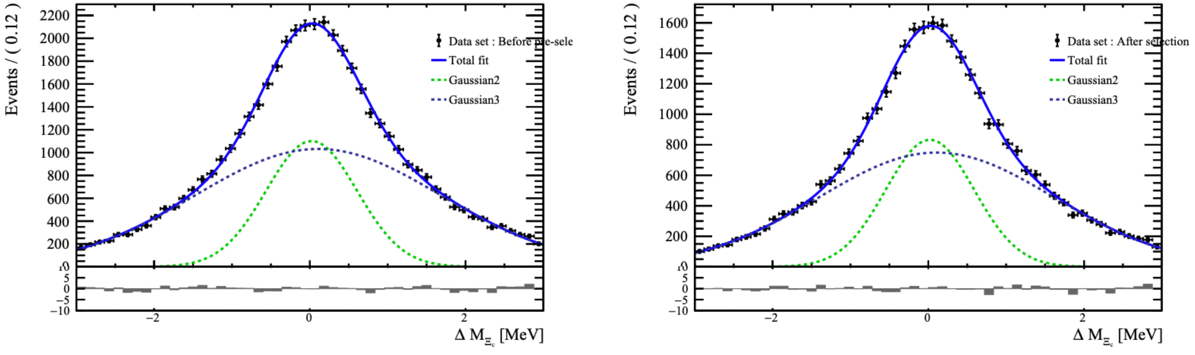
(a) $\Xi_b^0 \to D^+ \Lambda \pi^-$ channel, DD



(c) $\Xi_b^- \to D^0 \Lambda \pi^-$ channel, DD



(b) $\Xi_b^0 \to D^+ \Lambda \pi^-$ channel, LL



(d) $\Xi_b^- \to D^0 \Lambda \pi^-$ channel, LL

PDG Bias & Uncertainty

- *DecayTreeFitter* constrained D, Λ masses to known values in LHCb database

➢ Differences with PDG :

$$\Delta\mu = \sum_{D,\Lambda,\pi} (m_{PDG} - m_{LHCb})$$

➢ Uncertainties :

$$\sigma_{\mu_0} = \sqrt{\sum_{D,\Lambda,\pi} |\sigma_{PDG}|^2}$$

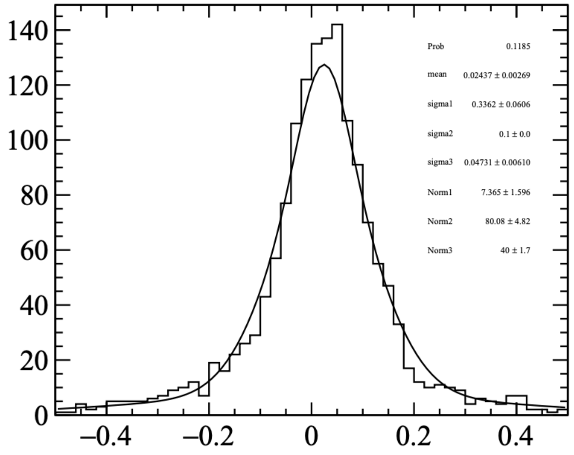
Overall bias $+0.04 MeV (-0.02 MeV)$, uncertainty $\pm 0.05 MeV (\pm 0.05 MeV)$ for Ξ_c^{**+} (Ξ_c^{**0})

Particle	PDG [MeV]	LHCb [MeV]	Particle	PDG [MeV]	LHCb [MeV]
Λ	1115.683 ± 0.006	1115.683	D^+	1869.66 ± 0.05	1869.62
D^0	1864.84 ± 0.05	1864.86	π^-	139.57039 ± 0.00018	139.57018

Momentum Scale

- Track momenta have been calibrated (MS)
  - With precision 0.03%
- Evaluated by varying calibration by $\pm 0.03\%$
  - Event-by-event mass difference is fitted (with triple Gaussian)
  - Maximum taken as uncertainties

Channel	MS varied by $+0.0003$	MS varied by -0.0003
$\Xi_b^0 \to \Xi_c{}^+\pi^-$	$0.008\,\mathrm{MeV}$	$-0.009\,\mathrm{MeV}$
$\Xi_b^- \to \Xi_c{}^0\pi^-$	$0.026\,\mathrm{MeV}$	$-0.024\,\mathrm{MeV}$



(d) -0.0003 scaled, $\Xi_b^- \to D^0 \Lambda \pi^-$ channel

Resolution Uncertainty

- Vary within $\mu_0 \pm \Gamma$ $1.25MeV \sim 1.40MeV$

then average between LL and DD

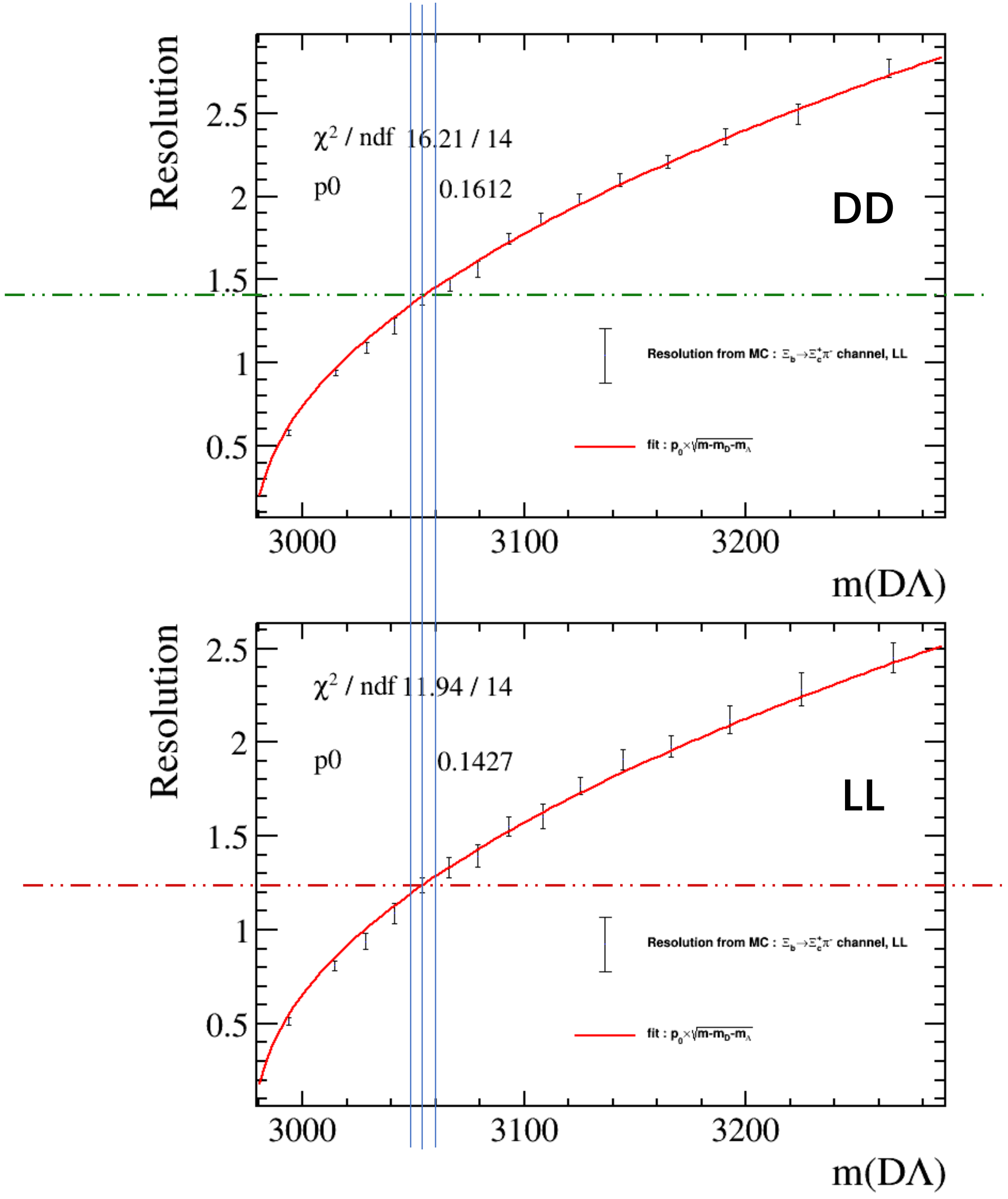
- Maximum differences taken as uncertainties

Tab.4 $\Xi_b^0 \to \Xi_c^{**+}\pi^-$ channel

Convoluted Resolution	$\Delta\mu_0$[MeV]	$\Delta\Gamma$[MeV]
Larger (1.40MeV)	<0.01	$\pm$0.08
Smaller (1.25MeV)	<0.01	$\pm$0.04

Tab.5 $\Xi_b^- \to \Xi_c^{**0}\pi^-$ channel

Convoluted Resolution	$\Delta\mu_0$[MeV]	$\Delta\Gamma$[MeV]
Larger (1.40MeV)	<0.01	$\pm$0.04
Smaller (1.25MeV)	<0.01	$\pm$0.01



MC Fluctuation

- MC integral over phase-space to implement signal efficiency
- Limited statistics in MC will introduce uncertainty to fit results
- Using bootstrap toy MC method

Tab.6 MC fluctuation uncertainties

Uncertainties	$\Delta\mu_0$[MeV]	$\Delta\Gamma$[MeV]	$\Delta\alpha$
$\Xi_b^0 \to \Xi_c^{**+}\pi^-$ channel	± 0.11	± 0.3	± 0.04
$\Xi_b^- \to \Xi_c^{**0}\pi^-$ channel	± 0.10	± 0.5	± 0.02

LL/DD Differences

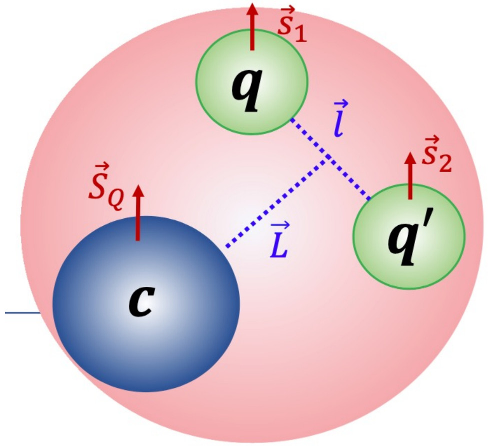
- In default fit, LL&DD samples are merged
- LL and DD samples are fitted simultaneously

Tab.10 LL/DD uncertainties

Uncertainties	$\Delta\mu_0$[MeV]	$\Delta\Gamma$[MeV]
$\Xi_b^0 \rightarrow \Xi_c^{**+}\pi^-$ channel	± 0.01	± 0.02
$\Xi_b^- \rightarrow \Xi_c^{**0}\pi^-$ channel	± 0.03	± 0.05

Contribution of $\Xi_c(3080)$

ρ modes: $l \neq 0$
λ modes: $L \neq 0$



- The $\Xi_c(3080)^{+/0}$ components are introduced to the amplitude model.
- $\Xi_c(3080)^{+/0}$ assumed to have $J = l_\lambda + s_c$, with $J = l_\lambda - s_c$ for $\Xi_c(3055)^{+/0}$
- With $l_\lambda = 2$, the J^P is fixed to $5/2^+$

Uncertainties of sWeights

- Uncertainty in Ξ_b mass fit can be introduced to amplitude fit
- Three variations of the $\mathrm{m}(\Xi_b)$ fit models are checked:
  - Extra component of $\Xi_b^- \to D^{*0}(\to D^0\gamma)\Lambda^0\pi^-$ partial reconstruction
  - Signal model :

$$Gauss + DSCB \to Gauss_1 + Gauss_2$$

  - Background model :

Exponential $\to$ 2nd order Chebychev polynomial

LS couplings

- Possible orbital angular momentums in $\Xi_b \to \Xi_c \pi$ weak decay.
- Only lower state considered in default model
- Alternative $l - s$ couplings are considered, with l expanded:

$$H^{A\to B+C}_{\lambda_B,\lambda_C} q^{l_{\min}} B_{l_{\min}}(q, q_0, d) \to \sum_{ls} g_{ls} \sqrt{\frac{2l+1}{2J_A+1}} \langle l0; s\delta | J_A \delta \rangle \langle J_B \lambda_B; J_C - \lambda_C | s\delta \rangle q^l B_l(q, q_0, d)$$

$$= \sum_{l=\frac{1}{2}+J_{\Xi_c}, J_{\Xi_c}-\frac{1}{2}} g_{l,s=J_{\Xi_c}} \sqrt{\frac{2l+1}{2}} \left\langle l0; J_{\Xi_c} \lambda_{\Xi_c} | \frac{1}{2} \lambda_{\Xi_c} \right\rangle q^l B_l(q, q_0, d)$$